WOODS HOLE OCEANOGRAPHIC INSTITUTION
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ANALYSIS & EXPERIMENTAL EVALUATION OF SINGLE POINT MOORED BUOY SYSTEMS

by

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TECHNICAL REPORT

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Approved for Distribution

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ABSTRACT

This report reviews the analysis and the evaluation of surface buoy systems performed in the Engineering Department of the Woods Hole Oceanographic Institution in 1968. The buoy systems considered are single point moored, taut and compound consisting of wire and synthetic ropes. The first part of the report describes the forcing functions and the system response as measured in situ during and after launching. The second part presents the results of the mooring line components testing and evaluation programs performed at sea or in laboratories. The third part briefly outlines the present development in telemetry transmission of scientific and engineering information. It is believed that this systematic engineering effort is an important factor in the continuous improvement of the reliability and performance of the deep sea buoy systems used in scientific measurements programs.

Acknowledgements

The cooperation of Messrs. R. Heinmiller and J. Gifford and their group in the setting and the retrieval of the deep sea moorings and of the shallow water experimental array and of Mr. O. Weyers in the reduction of the field data and in the performance of a significant number of tests, is gratefully acknowledged.

The assistance of Messrs. C. Collins and H. Armstrong in the development of the recording and telemetry systems was very helpful and is also gratefully acknowledged.

We wish to thank Mr. P. Stimson for his undaunted effort to observe a mooring in action from a deep submersible.

1. Forcing function and mooring line response

Static and dynamic loads are applied to deep sea buoy systems during and after deployment. The determination of these loads and of the mooring line response is a primordial factor of design improvement.

The acquisition of field data, especially long term series, is always difficult. Yet, in 1968, a substantial amount of engineering measurements was made in a number of experiments performed at sea in order to investigate the response of typical compound mooring lines to the launching transient during deployment, and to the static and dynamic loads after implantation. The parameters of interest and the experimental results are hereafter reviewed.

1.1 Launching transient

The technique used at the Institution for the deployment of deep sea moorings is the "buoy first, anchor last" method. A typical sequence of operations is: launching of the buoy with its instrumentation and the first shot of mooring line; paying out of the entire mooring line length and of the inserted instrumentation while underway; attachment of back-up system*, anchor release, and anchor; and finally launching and free fall of the anchor.

The different steps of the anchor free fall are depicted in Figure No. 1. During the process of launching and during the free fall of the anchor, the mooring line is submitted to a range of tension levels which are critical for the success of the subsequent implantation of the buoy system.

1.1.1 Parameters of interest

Transient tension - Synchronous tension values measured at different depths permit the determination of the stress level and the eventual

*Reference No. 4

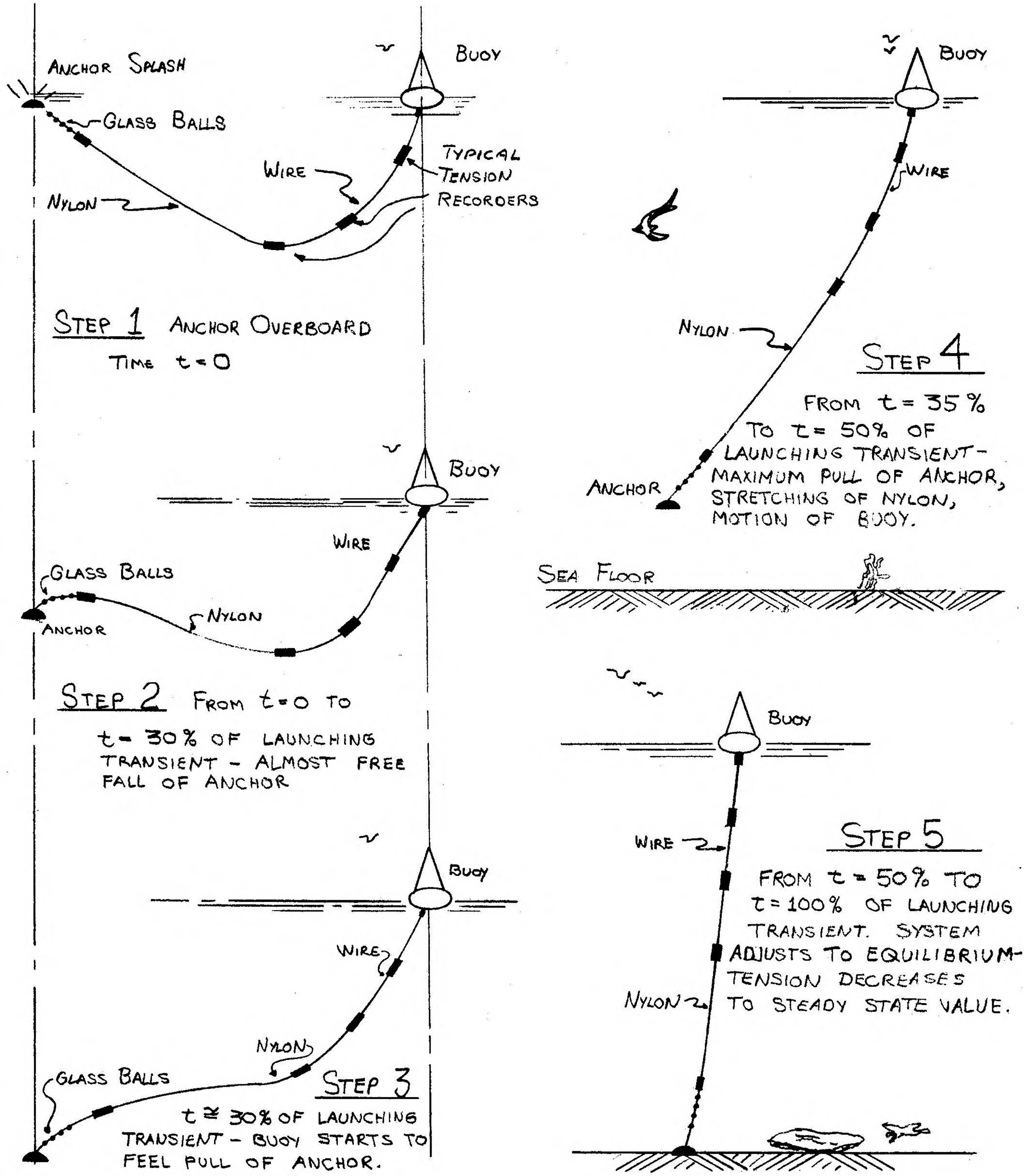


Figure 1. Typical Steps of Anchor Free Fall

reconstruction of line geometry during the free fall of the anchor.

Minimum tension levels - Slack conditions may occur during the paying out of the line and during the first part of the free fall of the anchor. Should this be the case, the line could coil back on itself and loops and kinks would form, permanently damaging the rope upon reapplication of tension. The detection of these conditions of slack is quite important in the evaluation of the launching process.

Maximum tension levels - The line progressively feels the weight of the anchor as it falls. A peak tension is eventually obtained just before bottoming. This maximum tension may be a large portion of the strength of the components in the line and its known value is useful in determining the optimum size of the components. Furthermore this peak load is a determining factor in the ensuing amount of stretch in the nylon and therefore of the minimum tension in the line. As further discussed in 2.2.1.3 the value of the peak load must be known to establish the elastic response to first loading of the synthetic fiber rope used in the mooring line.

Steady state tension - After bottoming, the buoy and the line continue to move to their equilibrium position and the tension eventually decreases to a steady state value indicative of average conditions encountered in long term moorings. The value of the tension immediately above the anchor is a measure of the pull of the line on the anchor. Its value is important in the selection of the anchor type and size.

1.1.2 Experimental results

Three short term engineering moorings (Stations No. 266, 271, and 278) were set and successfully retrieved in June, August and late September 1968. These three moorings with their instrumentation are depicted in Figures No. 2, 3 and 4. Tension recorders were placed immediately below the buoy, in the wire rope at 500 and 1000 meters, at the junction of the wire and the nylon ropes at 1500 meters, above the glass balls at 2500 meters and above the acoustic release of the anchor.

The tension was sensed and recorded during launching operations, during the free fall of the anchor, and for two additional days on site.

A typical tensiometer is shown in Figure No. 5. The tension sensor is a piston which compresses a given volume of oil when pulled by an external force. The resulting oil pressure deflects the needle of a Rustrak recorder through a Bourdon gauge and its mechanical linkage. The tension is recorded by clamping the needle to the recorder paper every two seconds. The ambient pressure is applied on both sides of the piston to compensate for depth effects.

Figure No. 6 shows a set of typical tension records. (Station 278).

Transient tension - The time between "anchor overboard" and the settling of the system to a steady state constitutes the launching transient. This time varies with depth and type of moorings. An average value for compound taut moorings set at station "D" is 60 minutes. The launching transient can be divided in three(3) phases: Free fall mode, pendulum mode, and relaxation phase.

The first phase lasts approximately 20 minutes or 33% of the transient. A sharp drop of tension is observed in all records at the time of the anchor launch. This drop serves as a time reference for the sequence of events at the different levels in the line.

PURPOSE OF TEST = MEASUREMENTS OF LAUNCHING TRANSIENTS (TENSION & ROTATION).

PROCEDURE = 7% STRETCH
LAUNCH SURFACE BUOY, PAY OUT MOORING LINE, ATTACH BALLS, LAUNCH ANCHOR - CHECK ANCHORING - RETRIEVE AFTER TWO DAYS ON SITE. TRIGGER RELEASE No. 1 FIRST.

EQUIPMENT = AS SHOWN

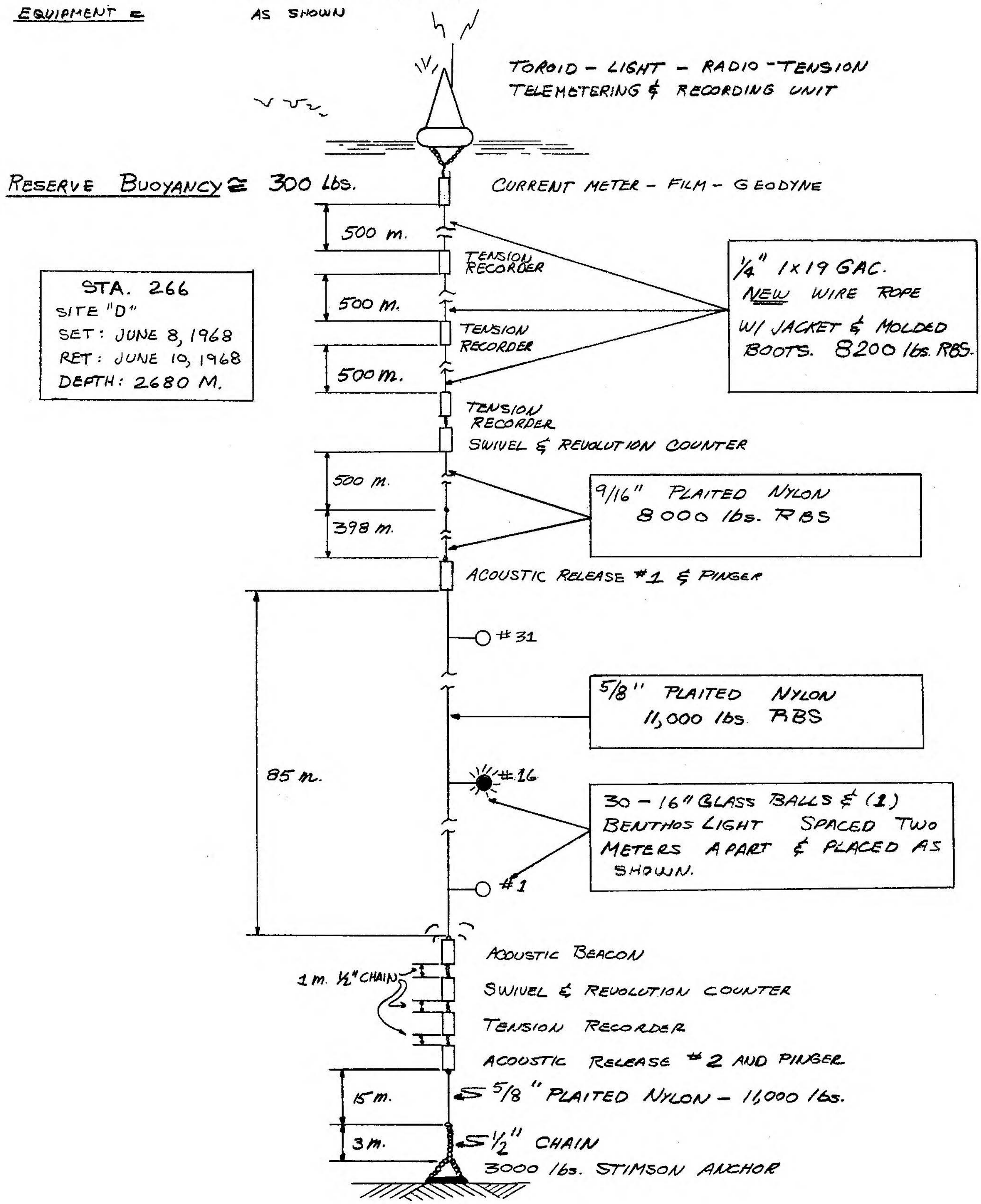


Figure 2. Station 266 - Short Term Engineering Mooring

PURPOSE OF TEST – MEASUREMENTS OF LAUNCHING TRANSIENTS (TENSION & ROTATION) 12% STRETCH

PROCEDURE – LAUNCH BUOY, PAY OUT MOORING LINE, ATTACH BALLS, LAUNCH ANCHOR, CHECK ANCHORING, RETRIEVE AFTER 2 DAYS ON SITE.

EQUIPMENT – AS SHOWN

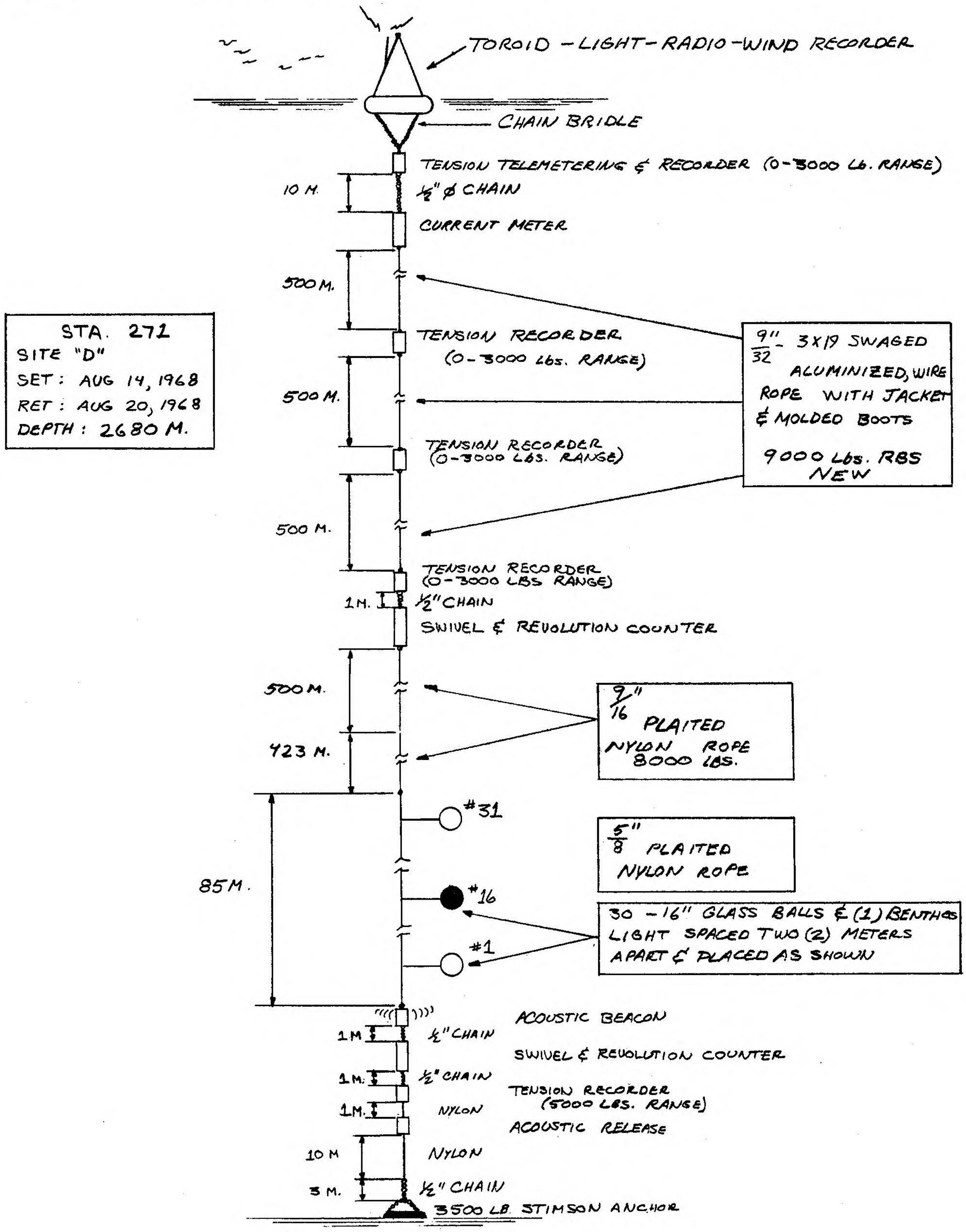


Figure 3. Station 271 - Short Term Engineering Mooring

PURPOSE OF TEST — MEASURE TENSION VALUES DURING LAUNCHING & AFTER WITH EIGHTEEN PER CENT OF STRENGTH 18% STRETCH

PROCEDURE — LAUNCH BUOY - PAY OUT MOORING LINE - ATTACH BALLS - LAUNCH ANCHOR - CHECK ANCHORING - RETREIVE 48 HOURS LATER.

EQUIPMENT — AS SHOWN

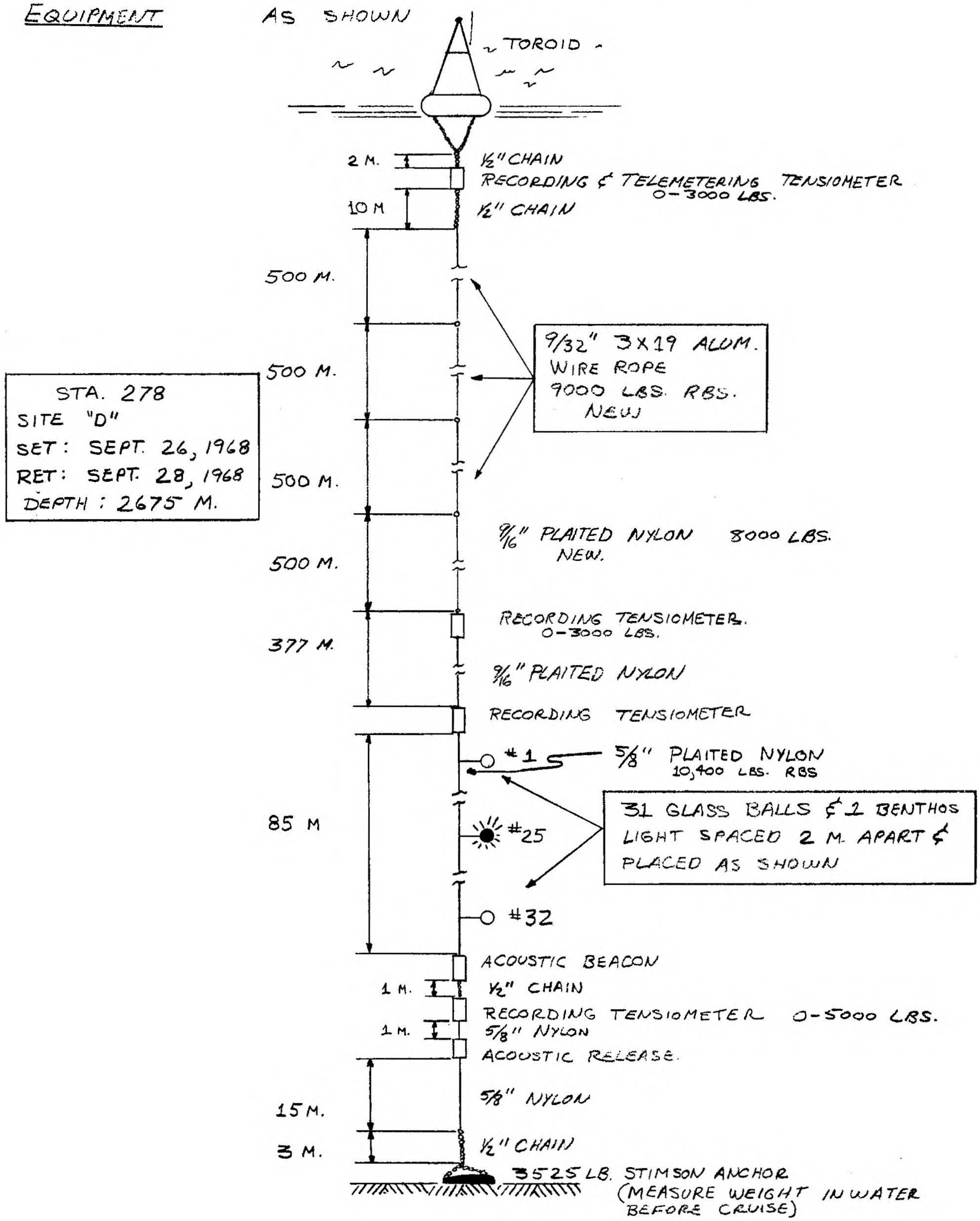


Figure 4. Station 278 - Short Term Engineering Mooring

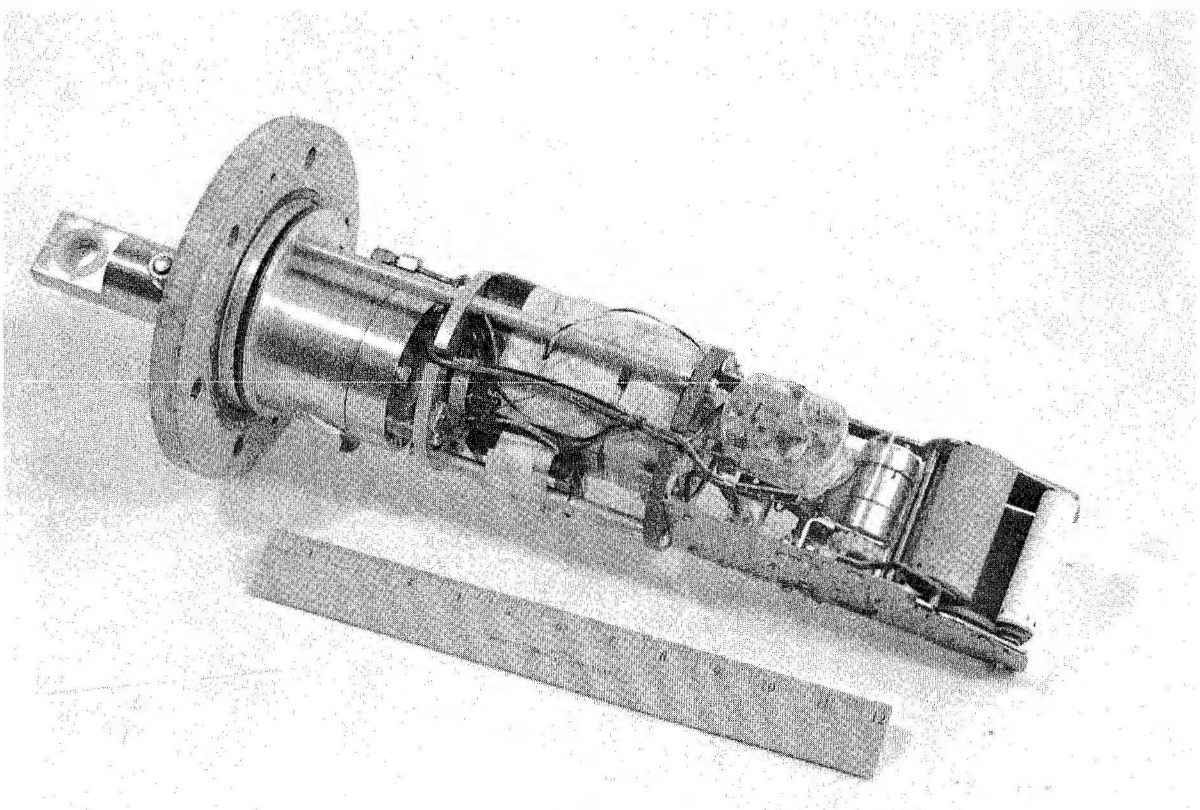


Figure 5. Tension Recorder

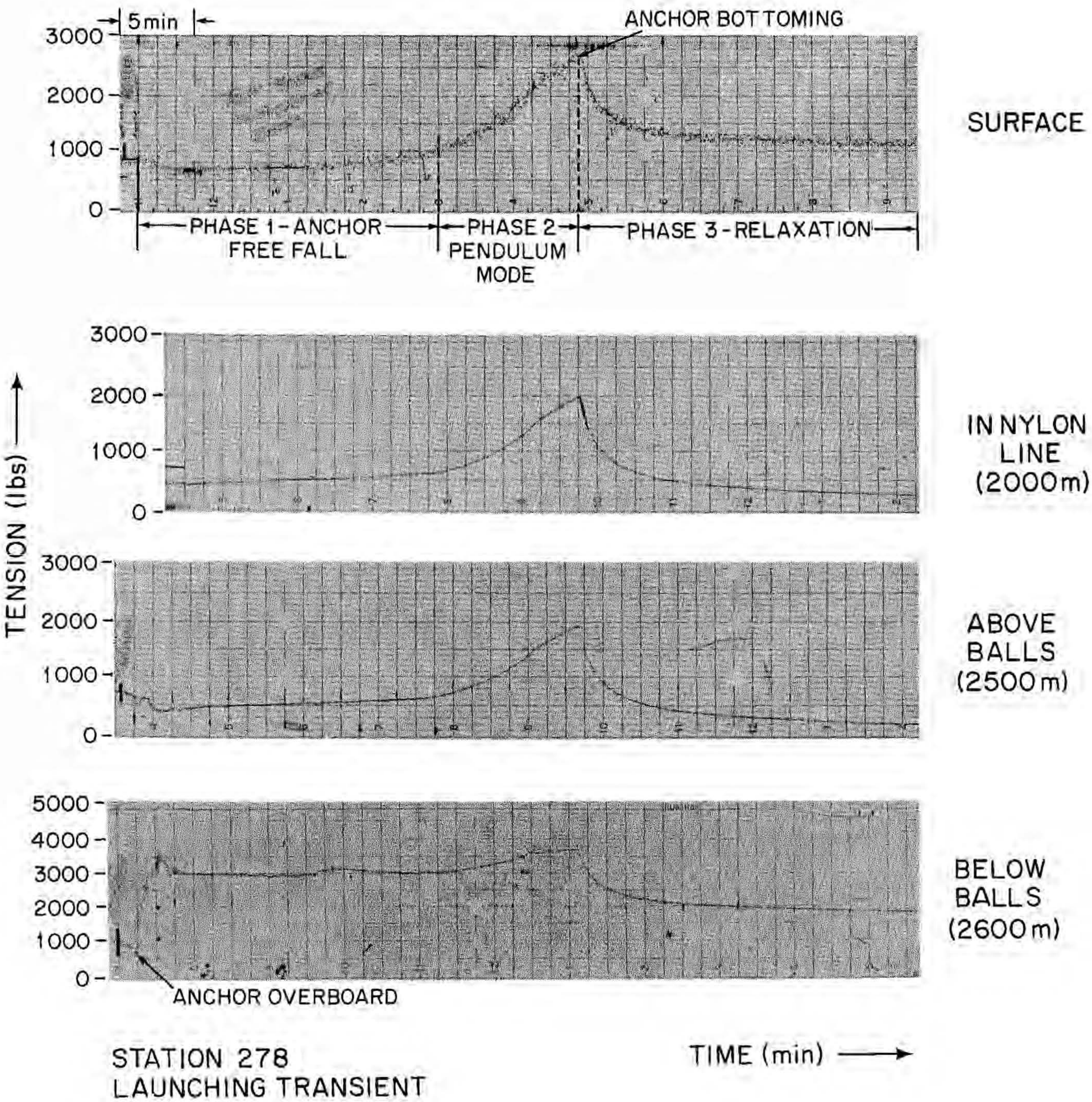


Figure 6. Station 278 - Tension Records

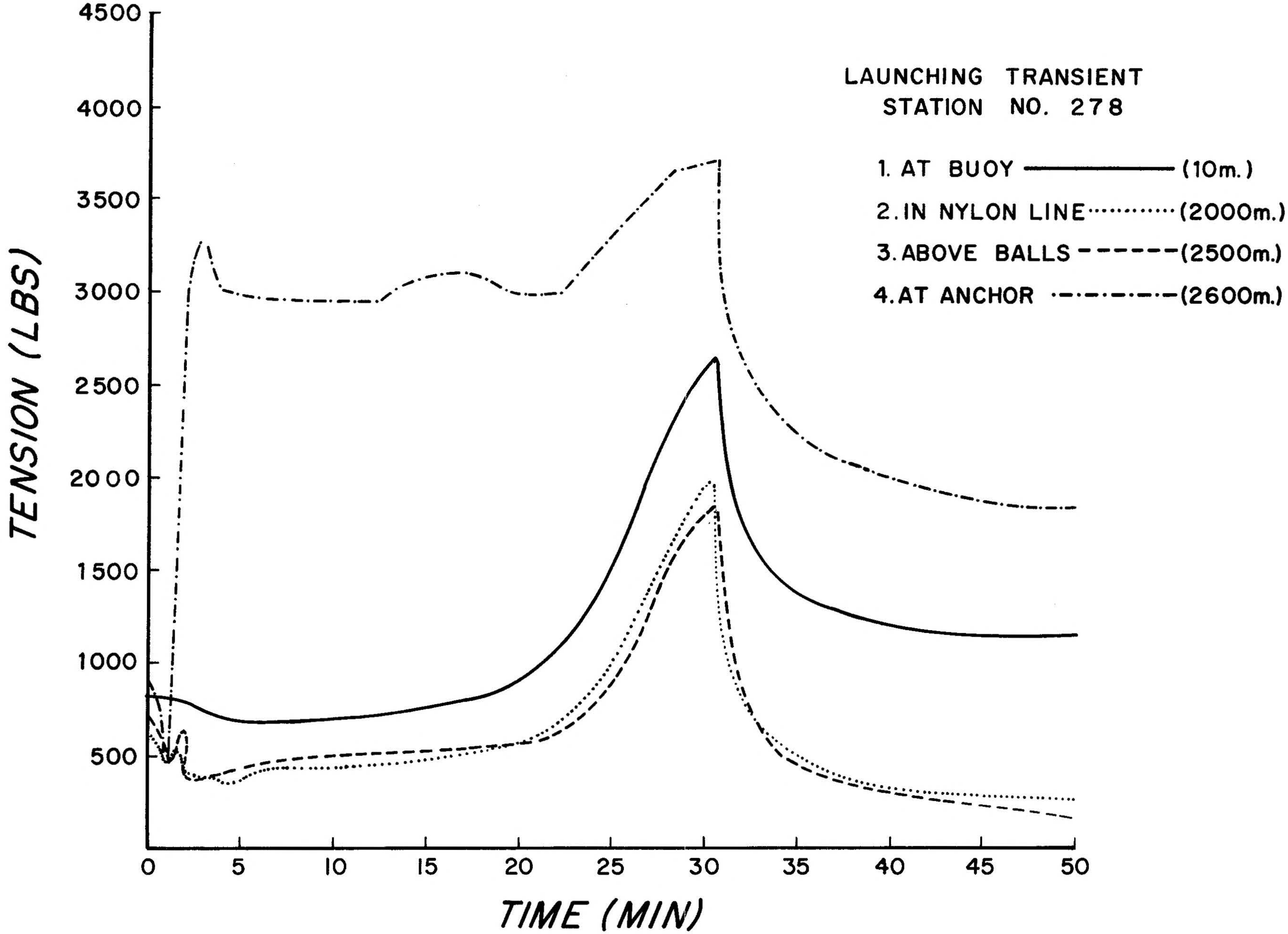


Figure 7. Station 278 - Diagram of Tension Versus Time at 4 Depths

Typical time variations of tension at different levels are shown in Figure No. 7 (Station 278). Curve No. 4 shows the tension at the anchor. It can be seen that this tension reaches a peak equal to the weight of the anchor and then decreases somewhat to a steady state value. At that time the system "anchor/glass balls" is free falling at a constant terminal velocity (See Figure No. 8).

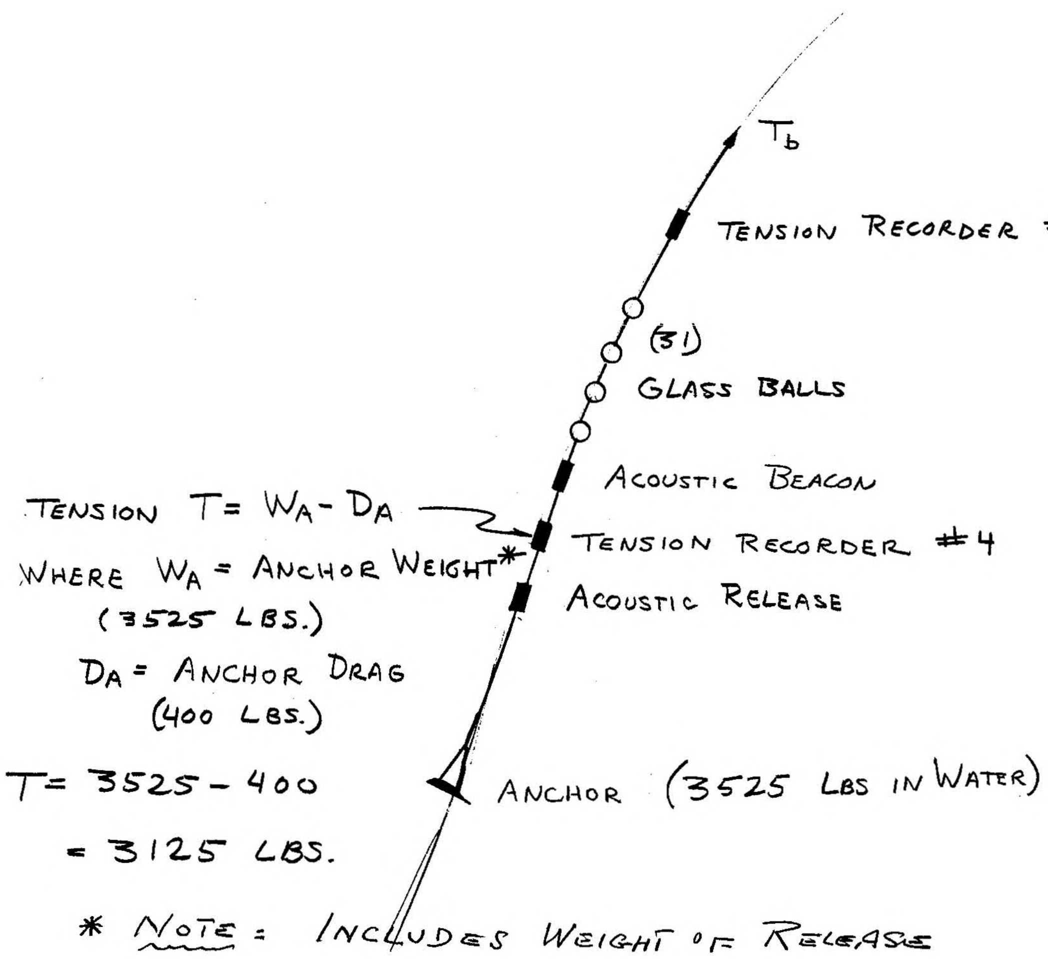


Figure No. 8 Tension at Anchor During Phase 1 - Station 278

The terminal velocity is reached only two minutes after anchor drop and its value is approxiamtely equal to 6 ft/sec. (See Appendix No. 5.1 for the theoretical derivation)

During the free fall of the anchor, the tension values at the buoy, and in the line remain essentially constant. The angle between the wire rope and the vertical at the buoy is approximately 40 degrees at the time of the anchor drop and decreases slowly as the anchor falls (See Appendix No. 5.1).

When the depth reached by the anchor is such that the mooring line is approximately straight, the pull of the anchor starts to be felt by the entire system and the second phase begins. The anchor swings somewhat like a pendulum in a complex path determined, in part, by the considerable elongation of the line and, in part, by the motion of the surface buoy. As the anchor slows down, the drag decreases and the tension between the anchor and the balls increases until a maximum value equal to the anchor wet weight is reached. This value is maintained while the mooring line swings and stretches until the anchor bottoms, (plateau of curve #4, Figures No. 6 & 7).

During the pendulum mode, the tension above the glass balls is given by

$$T_2 = T_1 + (W_a - B_b) \cos \alpha$$

where

T_2 = tension in the line during phase 2 at point of measurement

T_1 = tension at end of phase 1

W_a = wet weight of anchor

B_b = buoyancy of glass balls

α = F (t) = angle between line and vertical

When the anchor reaches the sea floor, α is minimum and the tension maximum. The largest value of this peak is at the surface where the weight of the components is maximum (largest T_1). The time of completion of the second phase is approximately 16% of the launching transient (or 10 minutes). The average time from anchor drop to anchor bottoming for moorings set at station "D" (2680 meters deep) is 30 minutes.

During the last phase of the transient the buoy pulled by the restoring force of the stretched line continues to travel towards its equilibrium position. Both the length of the line and therefore the tension decrease. A steady value, characteristic of the static response of the buoy system is finally reached and the launching transient is completed.

Significant tension levels - Sudden slacks and resulting low tension levels are single events extremely difficult to detect. They may occur between sampling times and their duration may be very short.

Low levels of tension have been observed during paying out of the mooring line, prior to anchor launching (zero tension, station No. 266). An effort to maintain tension at all times before the launch of the anchor is certainly indicated.

Values of tension near or equal to zero could not be detected during the launching transient.

Table No. 1 "Launching Transient, Significant Tension Values" lists the values of the peak tension and of the steady state tension obtained at several locations in the lines of the three short term experimental moorings.

TABLE NO. 1

LAUNCHING TRANSIENT, SIGNIFICANT TENSION VALUES

Station Number & Dates	Location of Tension Measurements in the Line	Peak Tension Measured (±50) lbs	Steady State Tension Measured (±50) lbs	Gravity Force at Location Computed (lbs)	% of Nylon Elongation (Steady State)	Tension Due to Nylon Prestretch		Safety Factor At Location		REMARKS
						Expected lbs.	Measured lbs	At Peak	Steady State	
266 Set= June 8, 1968 Retrieved: June 10, 1968	@ Buoy	2470	1150	1200	7% ?	-	50lbs	3.3	7.1	
	- 500 m	1800	700	740	9/16" Plaited			4.6	11.4	
	-1000 m	1650	480	470	Nylon			4.9	17.4	
	-1500 m (End of wire)	1250	230	160				6.5	35.7	
	-2680 m (Anchor)	4200	1450	1380				1.9	5.5	
271 Set= Aug.14-68 Retrieved: Aug. 20, 1968	@ Buoy	--	2175	980	12% ?		1000*	?	4.17	Beyond Scale
	- 500 m	2600	1650	620	9/16"			3.46	5.45	(9000 wire
	-1000 m	--	--	330	Plaited			?	?	(8000 Nyl
	-1500 m (End of Wire)	1875	950	70	Nylon			4.25	8.43	No Record
	-2680 m (Anchor)	3400	2500	1265				2.35	3.2	
278 Set=Sept. 26, 1968 Retrieved: Sept. 28, 1968	@ Buoy	2900	975	880	18% 18%	400	100	3.26	9.24	
	-2000 m	1900	140	30	5/8"			5.47	74.2	
	-2500 m (End of Nylon)	1700	85	0	Plaited Nylon			5.87	12.2	
	-2600 m (Anchor)	3600	1650	1310				2.9	6.3	

*Note: This high pretension value can be explained only by the uncertainty on the nylon length and history which could have resulted in a much larger % elongation than anticipated.

1.1.3 Experimental study of rotation characteristics

Turns can be induced in a mooring line during and after deployment. The number of turns due to unlaying of a free end rope under tension can be reduced if torque balanced constructions are used in the wire and in the fiber ropes of the mooring line. However, should an external torque be applied for long periods of time even torque balanced ropes would be damaged and fail. The twisting action introduces a torsional stress which may result in the formation of kinks and in the shifting of the load to only a small number of wires. If the number of turns is high enough, the strength of the rope may be reduced to only a small fraction (20% or less) of the original strength. In order to count the turns of the mooring line under actual conditions a special revolution counter was designed and built (Reference No. 5). The results obtained from the field pointed out the difficulties of registering the exact number of turns stored in the line and a better version of the instrument is being developed for future long term tests.

1.2 Quasi Static State

Taut surface moorings are submitted to the constant forces of initial prestretch weight and to the slowly varying drag forces due to the long period components of wind and current.

The quasi static state response resulting from the superposition of these forcing functions determines the shape of the mooring line, the extent of the buoy excursion, and the range of the average stresses in the line and attached instrumentation. The low response value corresponds to the equilibrium position and minimum stress level under still conditions, the high response value corresponds to the equilibrium position and maximum static stress level under steady conditions of flow. (See Figure No. 9)

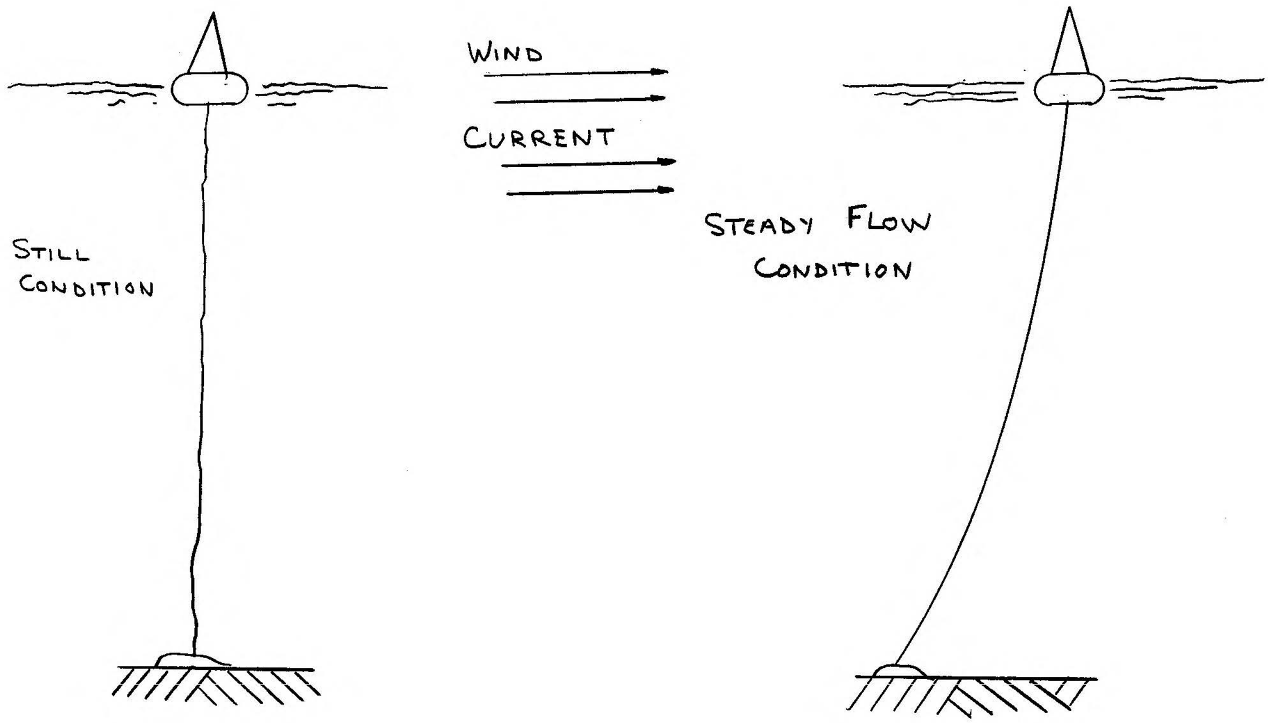


Figure No. 9 - Quasi Static State Response

1.2.1 Parameters of interest

Line Geometry - A knowledge of the buoy excursion and of the elapsed time between equilibrium positions enables the determination of the mooring compliance and the speed of motion of the mooring line and attached instrumentation. The compliance determines the dynamic response of the mooring line at high frequencies. The speed of the motion is of interest to the scientist who wants to filter out the "noise" of the current measurements. Buoy excursion and line shape are difficult to observe and measure in deep sea moorings. They can, however, be estimated by inserting the field data obtained from wind and water current meters and from tension recorders into computer programs recently developed for the study of the quasi static state of single point moored buoy systems. (Reference No. 7)

Minumum stress level - Low values of tension obtained at different depths are the result of the gravity forces at these depths and of the stiffness of the spring constant of the synthetic fiber part of the mooring line. (See Figure 10)

The minimum tension $T_{(y)}$ in still conditions is given by:

$$T_{(y)} = W_{(y)} + T_s$$

Where $W_{(y)}$ is the gravity force (positive or negative) @ the depth "y" and T_s is the tension due to elongation of the nylon, and is approximately given by:

$$T_s = T_u\, K \left(\frac{\Delta L}{L} - \frac{\Delta Lo}{L}\right)$$

T_u = Ultimate strength of nylon

K = Nylon spring constant

$\frac{\Delta L}{L}$ = % elongation on site

$\frac{\Delta Lo}{L}$ = intersection of linear part of elastic curve and % elongation axis (see Fig. 42)

Gravity forces (wet weight of components and buoyancy of buoyant elements) are readily established. If precautions are taken in the measurements of the mooring line and depth of the water, the elongation ΔL can be relatively well determined. Measurements of minimum tension should then lead to an effective value of the spring constant "K" by the use of relation above. An exact value of K would permit better evaluation of the response under steady flow condition and of the response to dynamic loading.

Furthermore, a knowledge of the minimum tension at the interface wire rope synthetic fiber has a particularly important practical aspect. At this depth the term W(y) may be very small and should the term T_s be small or zero then the tension holding the wire rope

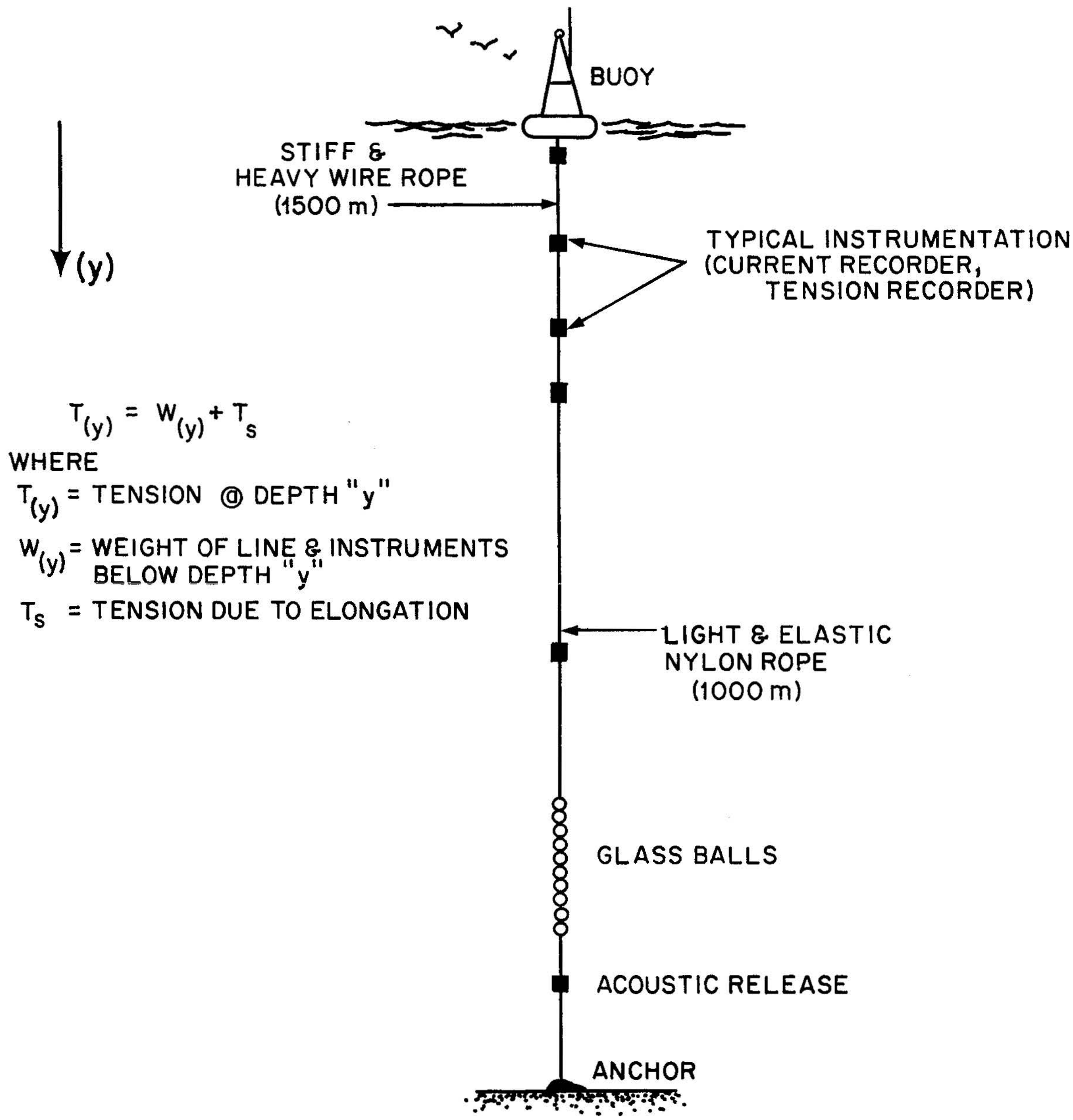


Figure 10. Taut Compound Mooring. Line in Still Conditions

would be zero and kinks could possibly form.

High Stress Levels - Under conditions of sustained wind and current the tension T(y) increases towards larger values. For surface following buoys the tension would fluctuate around a mean or DC level in a manner depicted in Figure No. 11.

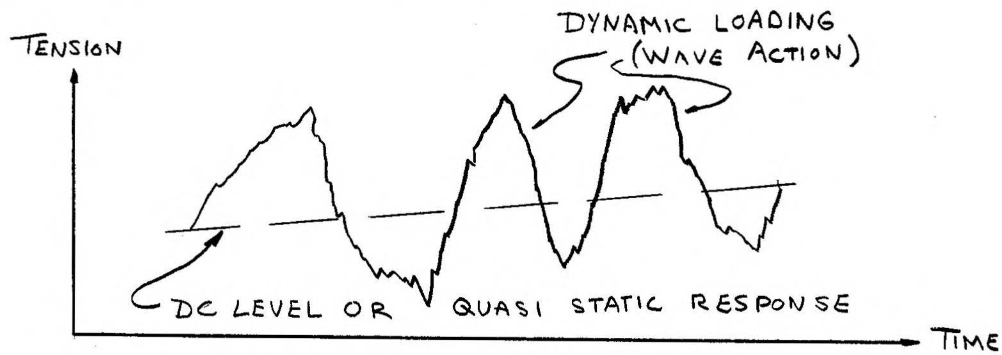


Figure No. 11. Tension variation around D. C. level

The theoretical value of this DC level of tension can be obtained from the solution of the two well known differential equations governing the response of cables in steady flow conditions.*

$$dT = (W \sin \phi - F_t(\phi))\, d_s$$

$$T\, d\phi = (R \sin \phi + F_n(\phi) + W \cos \phi)\, ds$$

where T = tension

dT = tension change

R = pressure drag when cable is normal to flow

F_t = tangential friction drag

F_n = normal friction drag

W = line density

ϕ = cable angle with the horizontal

$d\phi$ = change in cable angle

ds = cable element

Wind, surface currents, buoy shape, spring constant and depth determine the boundary conditions necessary for the solution.

*Reference No. 3

The analysis of the quasi static tension experimental data will establish the degree of correlation between theoretical analysis and empirical results. Should the correlation be good then the analytical tool could efficiently be used for predicting the response of mooring lines of other types and therefore be essential to their rational design. (Reference 8).

A practical and immediate result of this tension data is the determination of the effective quasi static safety factor, of the probability of creep of plastic components and of the value of the pulling force at the anchor.

1.2.2 Experimental Results

Four long term instrumented moorings were set in approximately 2600 meters of depth at Site D (39° N 70°W) in 1968. The detailed configuration of these moorings can be found in Section 2.1.1. These four moorings were fully recovered and the tension records were analyzed by engineers of the Ocean Engineering Department and scientists of the Physical Oceanography Department.* The most significant tension values are presented in Table No. II, "Long Term Moorings - Significant-tension Values".

A number of facts of immediate importance became apparent in the review of this tension data.

Minimum stress - Very low values of tension at the interface wire/nylon was noted on moorings of low nylon elongation percentage (7%). A substantial increase in the elongation percentage (12%) had little effect on the minimum tension which remained zero or very low. Such results could be explained only by either gross errors in nylon lengths or by hysteresis introduced in the first loading cycle. Lengths of new nylon acquired from the factory were measured and found to be well above the requested value, thus leading to

*Ref. No. 8

TABLE NO. II

LONG TERM MOORINGS - SIGNIFICANT TENSION VALUES

Station Number & Dates	Sea Conditions	Percent of Nylon Elongation	Location of Tension Measurements in the Line	Gravity Force @ Location (lbs)	Average Tension Due to Nylon Prestretch (lbs) (±50)	Quasi Static State Tension		Static Safety Factor	Extreme Values of Tension		Minimum Safety Factor	Maximum Range of Tension Fluctuations (lbs)	Attenuation of Tension Fluctuations
						Minimum (lbs) (±50)	Maximum (lbs) (±50)		Minimum (lbs.)	Maximum (lbs.)			
264 Set=April 20, 1968 Retrieved= June 9, 1968	Rough	7	@ Buoy End of wire @ Anchor	975 108 800	100	1200 20 900	2100 700 1350	4.7 11.4 8.0	600 0 875	2900 800 1500	3.3 10.0 6.6	850 188 130	4.5 1.45
269 Set=June 15, 1968 Retrieved August 23, 1968	Fair	7	@ Buoy End of Wire End of Nylon @ Anchor	728 40 80 1500	50	800 0 100 1680	1650 450 475 2100	6.5 18.0 17.0 5.0	320 0 0 1700	2200 1100 600 2200	5.0 7.2 13.0 4.5	720 100 70 50	7.2 1.4
275 Set=Aug. 22, 1968 Retrieved Sept. 27, 1968	Fair	12	@ Buoy End of Wire End of Nylon @ Anchor	824 52 0 1400	100	900 100 90 1600	1550 650 510 2100	6.4 16.0 21.0 5.0	375 80 50 1600	2150 700 600 2100	4.7 14.2 17.0 4.8	1100 150 100 30	7.3 1.5
279 Set=Oct. 1, 1968 Retrieved Dec. 11, 1968	Rough	18	@ Buoy End of Wire End of Nylon @ Anchor	837 30 0 1470	300	1050 300 220 1900	2400 1800 1650 3350	4.2 5.5 6.0 3.0	300 lbs 100 lbs 200 1900	3000+* 2400 1700 3400	3 (?) 4.1 5.7 2.9	1800 800 400 50	2.25 2.0

*Beyond Scale

errors in evaluation of elongation which resulted in no tension of the "taut" line.

Subsequent practice called for "in house" measurements and elongation values which were thus better controlled.

Response to first loading cycle was investigated and hysteresis established as further outlined in 2.2.1.3.

An 18% elongation was established for mooring No. 279, the resulting tension due to stretch was approximately 300 lbs., and the practical static spring constant K = 1 (linear approximation). The equivalent static spring constant determined in the lab tests was K = 2.6.

High stress levels

The four long term moorings had approximately the same wire rope ultimate breaking strength (10,500 lbs. ±5%) but different percentages of nylon elongation. The maximum values of quasi static state tension @ the buoy listed in Table No. II seem to indicate that under similar weather conditions the response of the moorings is independent of pretension. In other words the high and low values of "static" tension reached in bad or fair weather and the corresponding safety factors at the buoy are approximately the same for taut or slack moorings. On the other hand, moorings with the same prestretch will respond differently to different weather conditions as can be seen in the change of the safety factors of station 264 and station 269, both set with seven percent of elongation.

A comparison between values of tension at different depths seems to indicate that drag due to deep ocean currents have little effect on the tension at these depths. This is due to the low intensity of the current at Site 'D' and the small cross section of the wire rope in the region of stronger flow.

A correlation between weather conditions and tension positively indicates the preponderance of surface and near surface effects. Under high winds and correspondingly high surface water velocities the quasi static tension at the buoy of station No. 279 went from a low of 1100 lbs. to a high of 2400 lbs in approximately 3½ hours. It is interesting to note that this increase of tension is reflected all the way down to the anchor, which, at times, had an additional 1930 lbs to the 1470 lbs of pull of the back up system. The total pull then was only 125 lbs short of the anchor wet weight.

1.9 Study of Dynamic Response

In addition to near static tension forces due to pretension, gravity, wind and current drag, dynamic stresses are imparted to a buoy system by the motion of the surface float due to wave action and by the strumming of the line due to vortex shedding. Resonant conditions may cause large displacements and high stress levels and sharp transients may result in impact loads.

A knowledge of the dynamic stresses is an important factor for the design of improved buoy systems and for the selection of realistic test loads in the laboratory evaluation of the endurance limit of the mooring line components.

The response of the moorings to wave excitation was first investigated from long term tension measurements. The limits of this method prompted the development of an advanced dynamic sensing and recording system built and tested as hereafter described (1.3.2).

1.3.1 Long term tension measurements

The dynamic response of the four long term moorings set in 1968* could, to an extent, be evaluated from the tension records of the

*See Section 2.1.1

tensionmeter inserted in the mooring line.

The parameters which could be best established are the range of tension fluctuations, the attenuation of the surface excitation down the mooring line, the extreme values of tension over the period of implantation. These results are presented in Table No. II, "Long Term Moorings. Significant Tension Values".

Due to cyclic excitation at the water surface, the tension in the line fluctuates around the quasi static state mean. The range of this fluctuation is difficult to predict theoretically, due to the non-linearity of the system excitation and response. Theoretical derivations based on the propagation of elastic waves in deformable bodies neglect the compliance of the mooring line which adjusts its geometry to changes in tension. (It is not an incline bar). Derivations based on the analysis of the geometry changes and resulting stress levels are theoretically correct. They would require the experimental determination of a number of parameters (added mass, effective drag coefficient, restoring constant) and the analytical solution would involve complex programming.

The experimental attenuation coefficient, or ratio between two values of the dynamic range is a function of the mooring material and possibly the mooring rigidity. It is interesting to note that under severe weather conditions the surface excitation is felt all the way down where it can be as much as ¼ of the surface range at Site D. However, it is attenuated below the balls of the recovery system which act as a lo-pass filter.

Extreme tension values show that the moorings undergo severe fatigue loadings and that the static safety factors may be reduced considerably.

1.3.2 Mooring Dynamic Response Sensing and Recording System

Tension data acquired with the instruments used in 1968 on long term moorings were limited by the instrument range, the sampling rate and the chart speed. Large values of tension and impact loads could escape detection, and the instantaneous response could not be established. Furthermore, the acceleration and the displacement of the line in any one of the three cartesian references could not be investigated.

In order to better evaluate the dynamic response of the line a new instrument was designed, constructed and tested at sea. Three additional units are being completed and will soon be used in a comprehensive program of synchronous mooring line dynamic measurements.

1.3.2.1 Instrumentation

An instrument was designed and a prototype constructed to internally record mooring tension, acceleration in two orthogonal axes normal to the mooring line, time and a reference frequency. The recorder and all instrumentation is mounted in a pressure case 52½" long and 7" ouside diameter, approximately the same dimensions as the current meter used at WHOI. A strain gage tension cell placed a one end of the instrument case senses mooring tension. Two linear strain gage accelerometers mounted within the instrument case respond to accelerations in the X & Y planes. The ouputs of these sensors are fed to voltage controlled oscillators (VCO's) causing their frequency to vary in accordance with the measurands. The VCO ouputs, together with time signals and a reference frequency are frequency multiplexed and applied to a magnetic tape recorder. Figure 13 shows, in block arrangement, the signal paths from sensors to the tape recorder.

The timing and reference signals are derived from a temperature controlled crystal oscillator with timing accuracy sufficient to correlate tension events measured and recorded at different locations. The instrument is presently programmed to sample for twenty minutes every twenty-four hours with sufficient tape to run for 96 minutes.

Tension Cell - The tension cells were built to specifications by the Massachusetts Institute of Technology, Instrumentation Laboratory. Each cell is constructed of stainless steel with a full scale range of 4000 pounds. Strain gages are used as the sensitive element to provide a short response time and high resolution. Temperature and torsional compensation is provided by the strain gage mounting geometry and bridge configuration. The strain gages form a bridge circuit which is supplied with regulated DC voltage. The sensitivity is 10 microvolts output per volt excitation per pound tension. Each sensor is pressure compensated to remove the biasing effect which increasing depth would have upon it.

Accelerometers - Consolidated Electrodynamics Corporation bonded strain gage accelerometers are used to provide high resolution sampling of accelerations of the instrument case due to strumming. Two accelerometers with a range of ±1 g are mounted with their sensitive axes orthogonal to each other and normal to the instrument case. Additional units

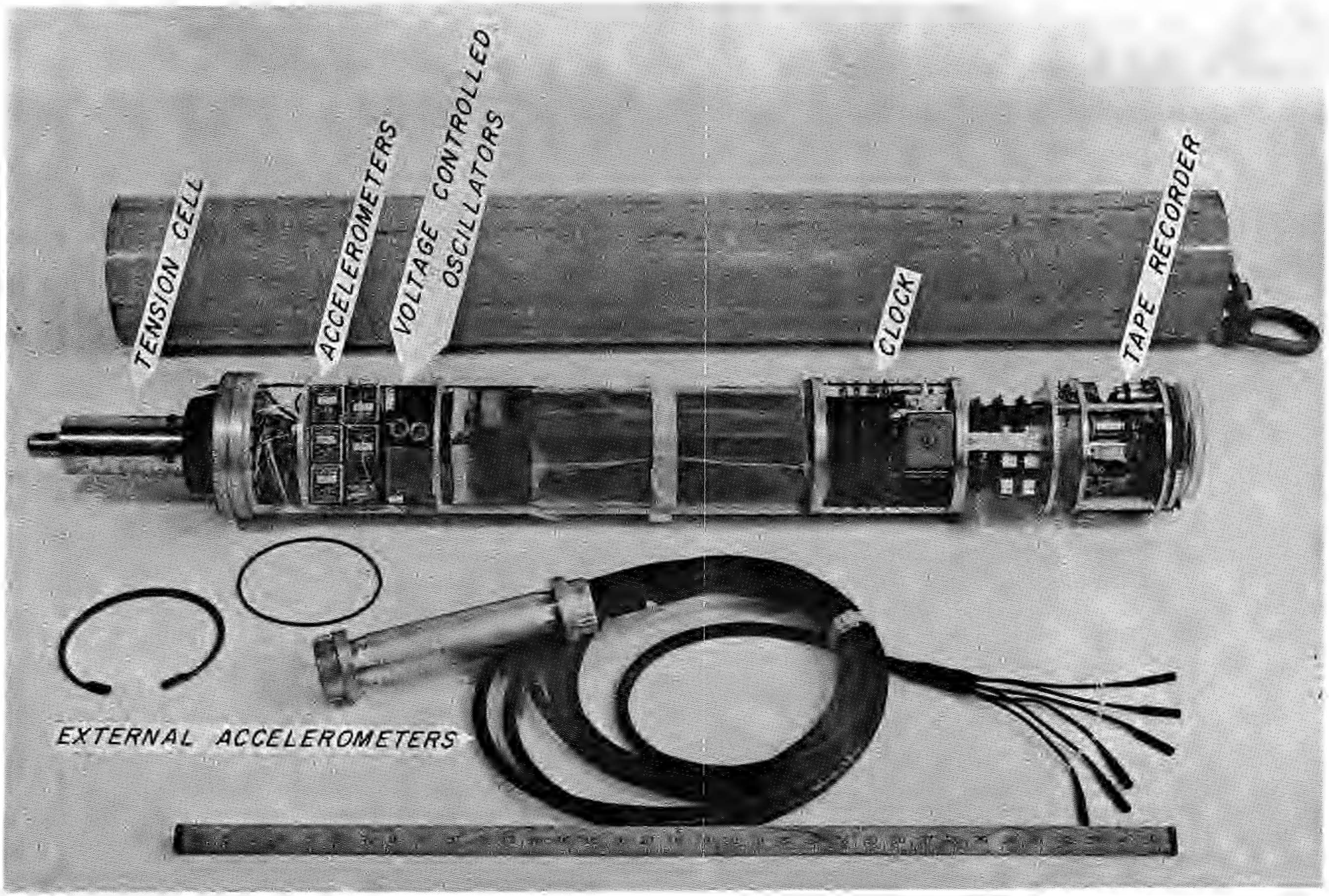


Figure 12. Tension and Dynamic Response Sensing and Recording Instrument

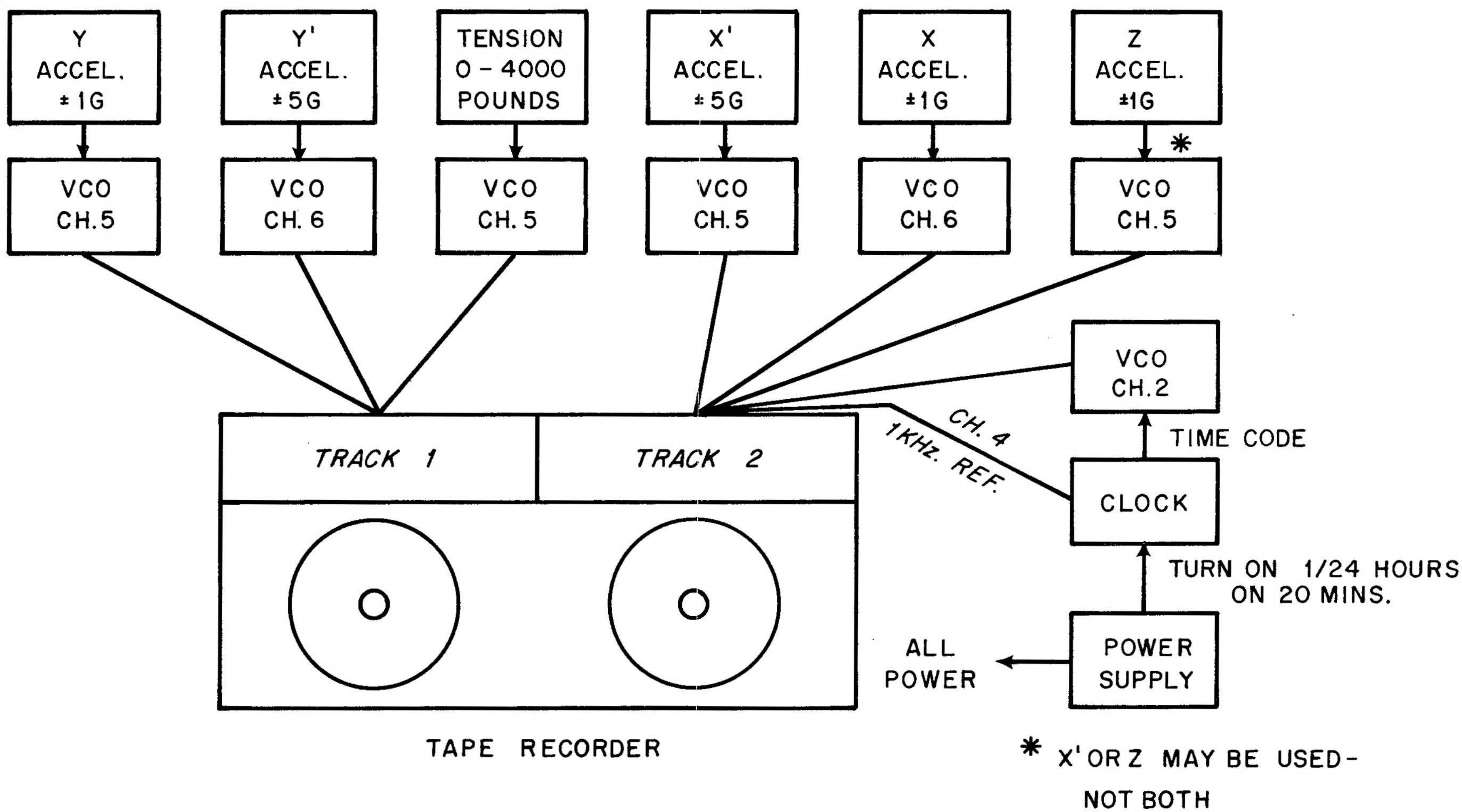


Figure 13. Signal Paths - Tension/Vibration Recorder

with a range of ±5 g, encased in a low-mass pressure housing, will be attached to the mooring line itself, some distance from the instrument case, to measure the line strumming amplitude and frequency. Two of the instruments contain an accelerometer measuring acceleration in the Z axis. These units have a full scale response of ± 1 g. One will be used to obtain the forcing function at the top end of the mooring line due to surface wave action. The other will permit measurements of the propagation time, phase, and the attenuation or magnification of these accelerations as a function of depth. The accelerometers are electrically configured to a bridge circuit which is supplied with regulated DC voltage.

Voltage Controlled Oscillators - A frequency multiplexing method of recording sensor output is utilized to record the data on magnetic tape. Each sensor output effectively modulates the input to a voltage controlled oscillator whose frequency varies with this input change. Voltage controlled oscillators (VCO's) were selected within standard bands with a frequency deviation of ±7.5% of the center frequency. In order to obtain sufficient recording time a slow speed recorder was required (1-7/8" sec), which severely limited the highest frequency which could be recorded. The choice of sub-carrier frequencies was then a compromise between the highest anticipated data frequency and the tape recorder response at the higher frequencies. IRIG* channels 2 through 6 were chosen (Table III) to

*Inter-range Instrumentation Group

TABLE NO. III

CHANNEL SPECIFICATIONS

TAPE TRACK NO.	FUNCTION	IRIG CHAIN	CEN FREQ (Hz)	LOWER DEVIATION LIMIT (Hz)	UPPER DEVIATION LIMIT (Hz)	NOM FREQ RESPONSE (Hz)	NOM RISE TIME (MSEC)	MAX FREQ RESPONSE Hz	MIN RISE TIME (MSEC)
1	Tension	4	960	888	1032	14	24	72	4.86
1	Acceleration (Y)	5	1300	1202	1398	20	18	98	3.60
1	Acceleration (Y')	6	1700	1572	1282	25	14	128	2.74
2	Reference Frequency	4	960	888	1032	14	24	72	4.86
2	Time Marks	2	560	518	602	8	42	42	8.33
2	Acceleration (X)	6	1700	1572	1282	25	14	128	2.74
2	Acceleration (X')	5	1300	1202	1398	20	18	98	3.60
2	Acceleration (Z)*	5	1300	1202	1398	20	18	98	3.60

*Acceleration X' or Z may be used, not both.

support the required data. The higher channels, with larger bandwidths are used for the acceleration channels where frequencies up to 15 Hz may be measured. Errors due to frequency drift of the units selected are not expected to be greater than 1%.

Tape Recorder - The tape recorder for the instrument was designed to W.H.O.I. specifications by Wm. E. Swift Co. The frequency response is nearly flat over the range of sub-carriers used, (518 to 1398 Hz). A recording speed of 1 7/8" per second provides a total recording time of 96 minutes. Wow and flutter components were measured to be less than 3% RMS within a 7½% data band width of the reference frequency channel. Speed error compensation during processing reduces the noise contribution of this signal to less than 1%. The effects of slow speed changes during the record are eliminated by this compensation.

Two tracks are used with three frequency multiplexed sub-carriers on each track. One of these tracks also contains an accurate reference frequency (1000 Hz) obtained from the crystal clock.

Clock - A temperature controlled crystal oscillator is used as the basic timing source for the instruments. The drift rate is less than 5 parts in 10^{-9} per day which represents a timing error of 3.5 milliseconds in 4 days. The basic crystal frequency is counted down by a series of counters to provide a 1000 Hertz sine wave for a reference frequency, one second, one minute and 10 minute pulses for the timing channel and an output which turns the tape recorder and electronics on for precisely 20 minutes once per twenty-four hours. A reset terminal is brought out through each instrument end cap. These terminals can be wired together and connected to a reset generator to permit precise initial synchronization of all instruments. Four twenty minute recordings are thus taken over a period of four days.

1.3.2.2 Data Reduction

Arrangements were made through ONR to process the tape records at the data processing facility of the Convair Division of General Dynamics, San Diego, California. Facilities exist there to filter and discriminate the multiplexed signals and to display them on a high speed graphic recorder. Through the use of the reference frequency, compensation for tape recorder speed errors is applied to correct the data. Figure 14 shows the reduction of spurious signals due to wow and flutter by this compensation. Facilities are also available to digitize certain segments of each record and to include a standard format time derived from our basic clock output. To date we have requested and received only graphic records of each run to evaluate instrument performance and to determine the scaling factors for the experiment. Upon completion of the remaining three instruments and their deployment and retrieval, portions of each record will be digitized using a format compatible with the W.H.O.I. Sigma 7 computer.

The experimental program will supply the data needed

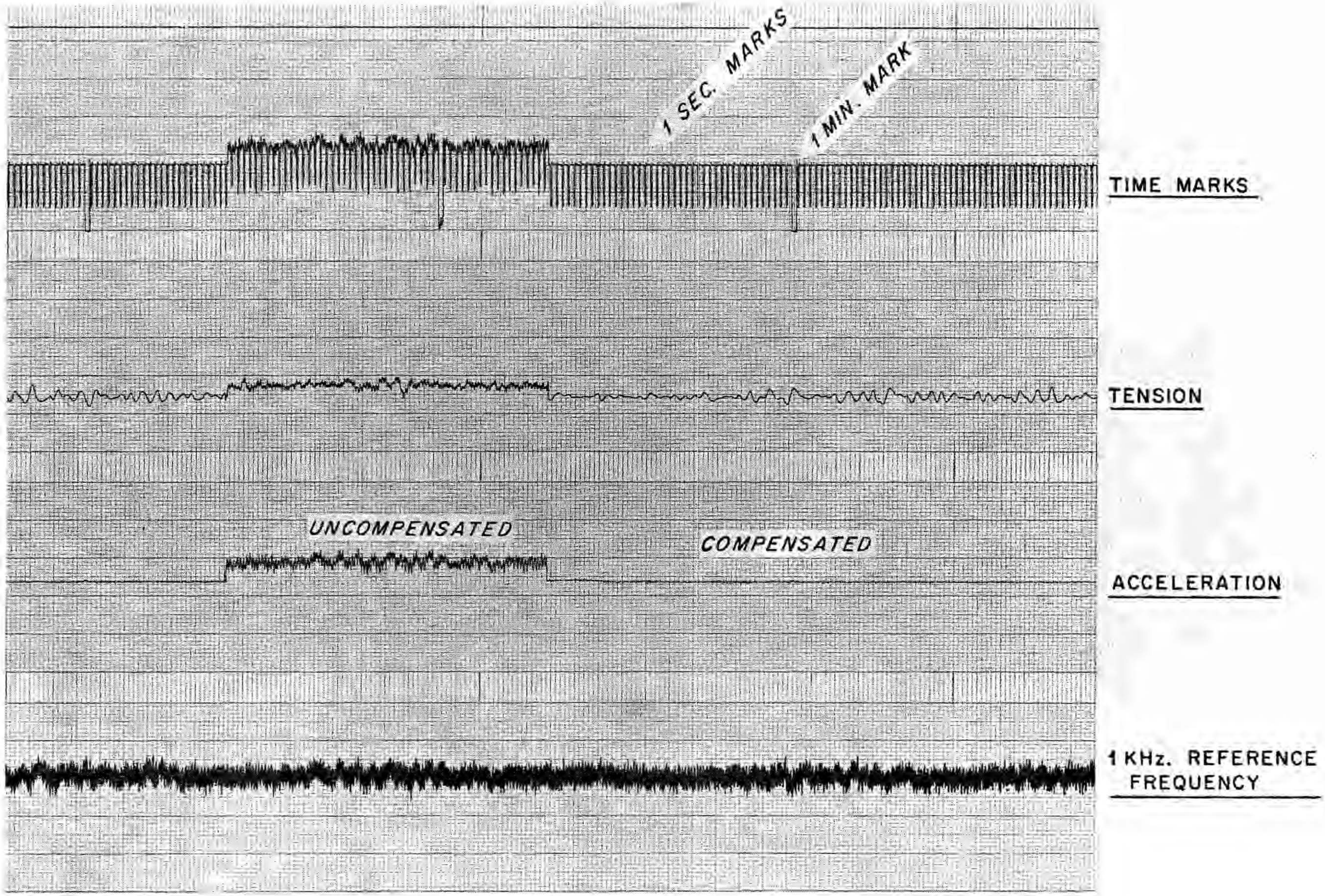


Figure 14. Speed Error Compensation

to permit an analytical approach to a mathematical model to be formulated. The experimental data will provide means, variants and spectra of the tension values and cross-correlation of these values between instruments. Vibration frequency and amplitude of both the instrument cases and mooring wire may also be determined.

1.3.2.3 Experimental Results

The test tape was run to determine the system capability, including noise. Each accelerometer was rotated 180° to provide ± 1 g acceleration values, which were recorded on the tape recorder. The complete instrument was then installed in a tensile testing machine and increments of tension to 4000 pounds applied while making a recording. This tape was subsequently processed at Convair. System noise due to wow and flutter components in the tape recorder were considered too high (3% of full scale). Modifications were made to the tape recorder to reduce this value. Other minor troubles were noted as a result of processing the tape, which were corrected.

The instrument was next placed at 500 meters on mooring Station 273 in August 1968 for evaluation in the ocean. The instrument and mooring was retrieved in good condition after three days and the tape processed at Convair. An intermittent plug connection in the clock caused the tape recorder to come on more often than once per twenty-four hours and to stay on less than the required 20 minutes. Values of acceleration were low, about equal to system noise. The accelerometers were replaced with more sensitive units

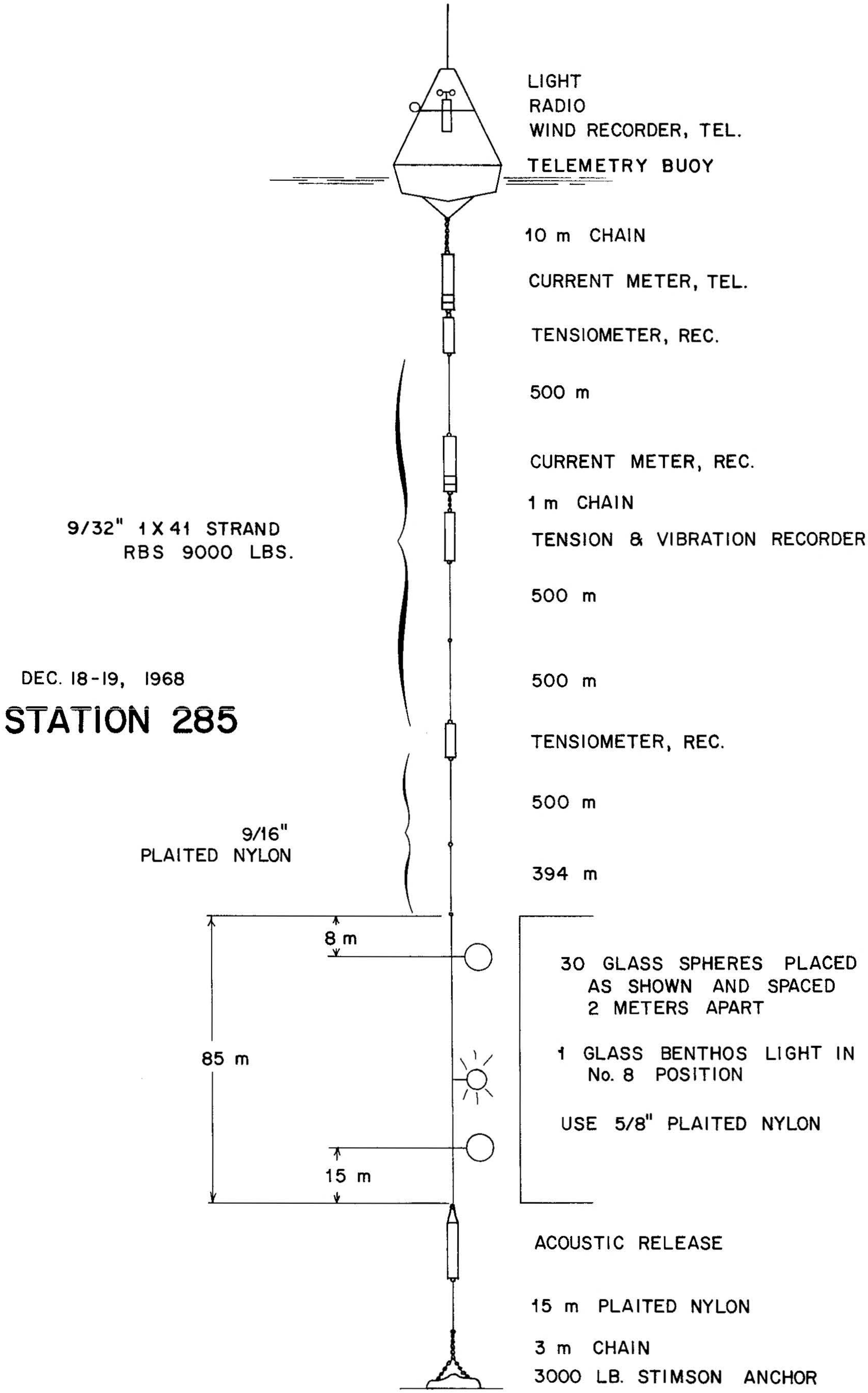


Figure 15. Mooring 285 Schematic

which had been on order. Tension values were within the expected range and showed response characteristics due to surface wave excitation.

Orders were then placed for components for three additional units to provide the capability of coherent tension observations and vibration at four points in a mooring.

A second test of the prototype instrument at sea was made on December 18 and 19 on mooring station number 285. This mooring consisted of a 12 foot discus surface buoy* which telemetered surface current speed and direction. A schematic diagram of the mooring is shown in Figure 15. Incremental recording tension recorders were placed at the surface and at 1500 meters. A current meter and the tension vibration recorder were located at 500 meters. The mooring was compound consisting of 1500 meters of 9/32" wire rope and 994 meters of 9/16" plaited nylon. The nylon was precut so that its' length was 159 meters short of the desired mooring depth (2680 M). This required stretch of the compliant portion of the mooring calculated (after allowing 7% for permanent elongation) to give a remaining tension of 600 pounds in the nylon. (See Appendix 5.2).

Figure 16 shows the tension variation at the surface and at 1500 meters during launch and bottoming of the anchor. (Anchor - last launch).

The tension/vibration recorder obtained two, twenty minute records, one on December 18 and another on December 19. The acoustic release was fired six minutes before

*See Appendix No. 5.5 Telemetry Buoy Data Sheet

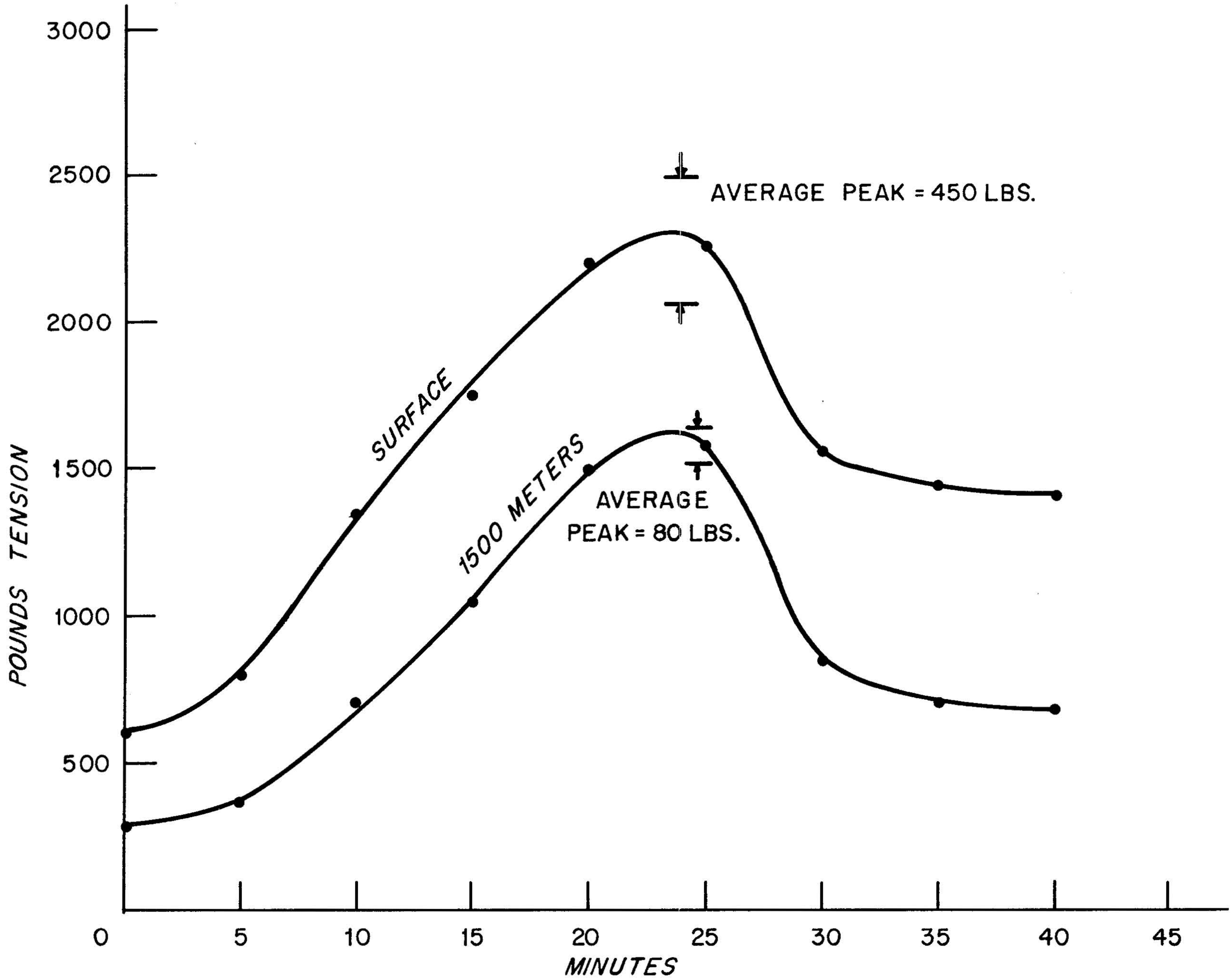


Figure 16. Launch Transients

the end of the second recording to include the resultant tension drop in the record. Figure 17 shows the twenty minute interval including anchor release of the recording tensiometers at the surface and at 1500 meters. Inspection of the 1500 meter tension value before release indicates how closely the calculated tension was achieved. The tension after release, about 90 pounds, represents the wet weight of the nylon and hardware below the tensiometer.

A section of the tension/vibration instrument record at 500 meters is shown in Figure 18. The tension drop at release from 1100 pounds to 600 pounds taking about 11 seconds to settle out can be seen. The average current value as obtained from the recording current meter at 500 meters during this latter run was 16.6 cm/sec.

Figure 19 depicts the tension values observed at three points in the mooring during the twenty minute run on December 18, 1968. The mean tension values and average of the peaks are shown as recorded by instruments at the surface, 500 meters and 1500 meters. Values from the bottom end of the wire rope (1500 meters) to the top of the back-up flotation system are estimated and shown as dotted lines. This 600 pounds was the calculated value of tension at this point due to nylon stretch. Thirty, sixteen inch glass spheres below this depth provide a nearly constant tension at the anchor of 1500 pounds, plus that resulting from drag forces. The average current at 500 meters during this sampling period was 15.5 cm/sec. Lateral motions of the case were monitored by the X & Y plane

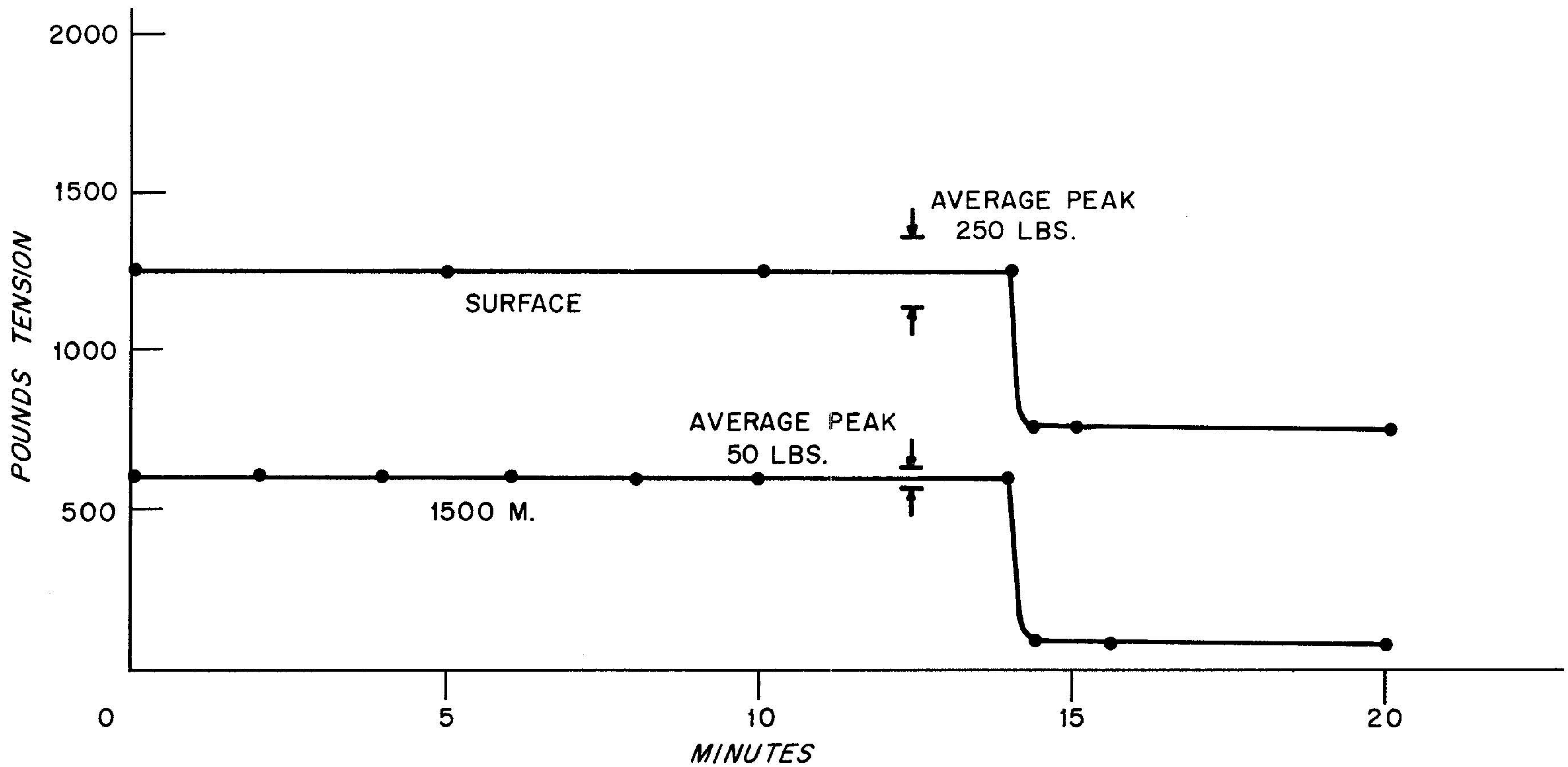


Figure 17. Tension Values During Anchor Release

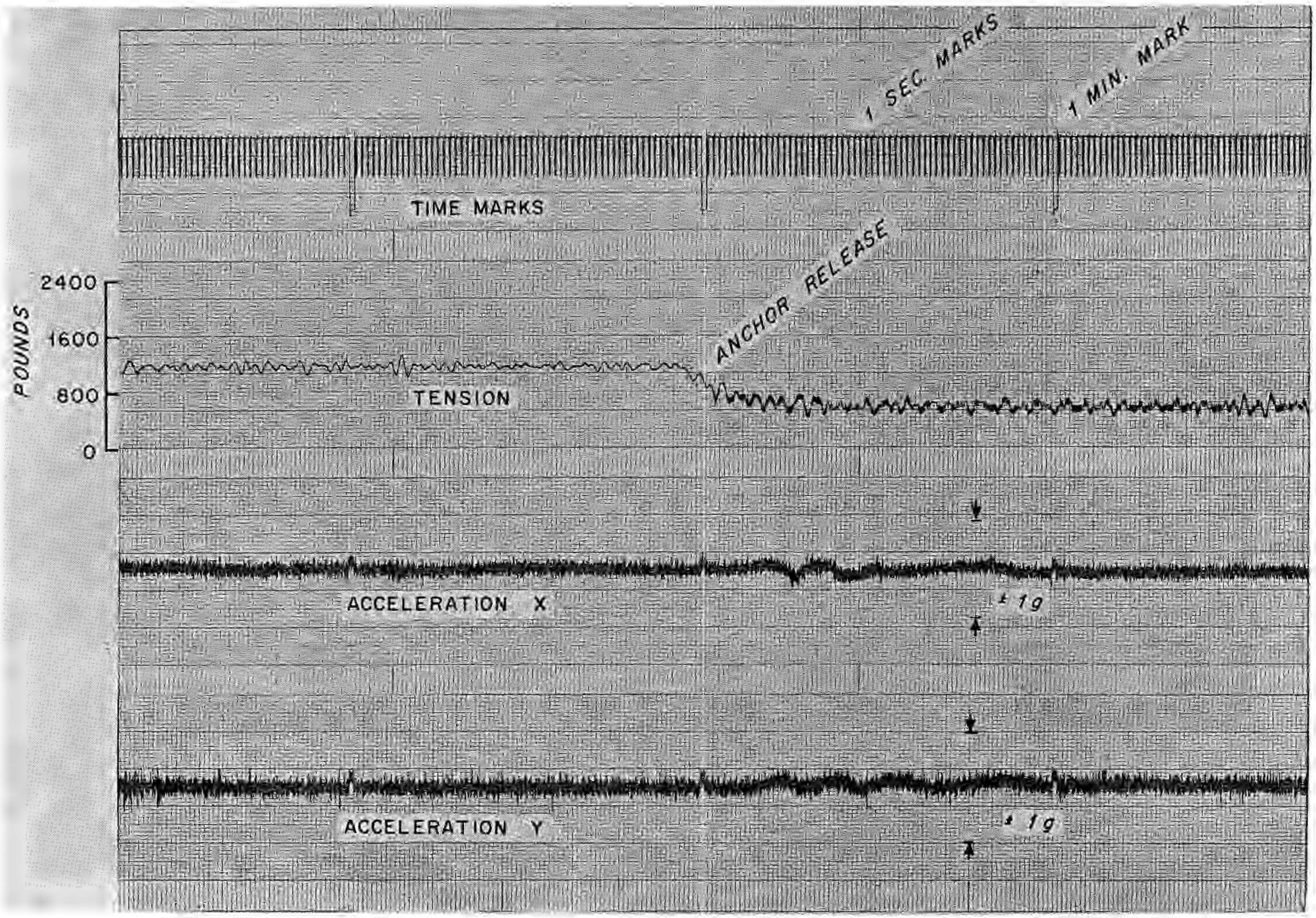


Figure 18. Tension/Vibration Record During Anchor Release

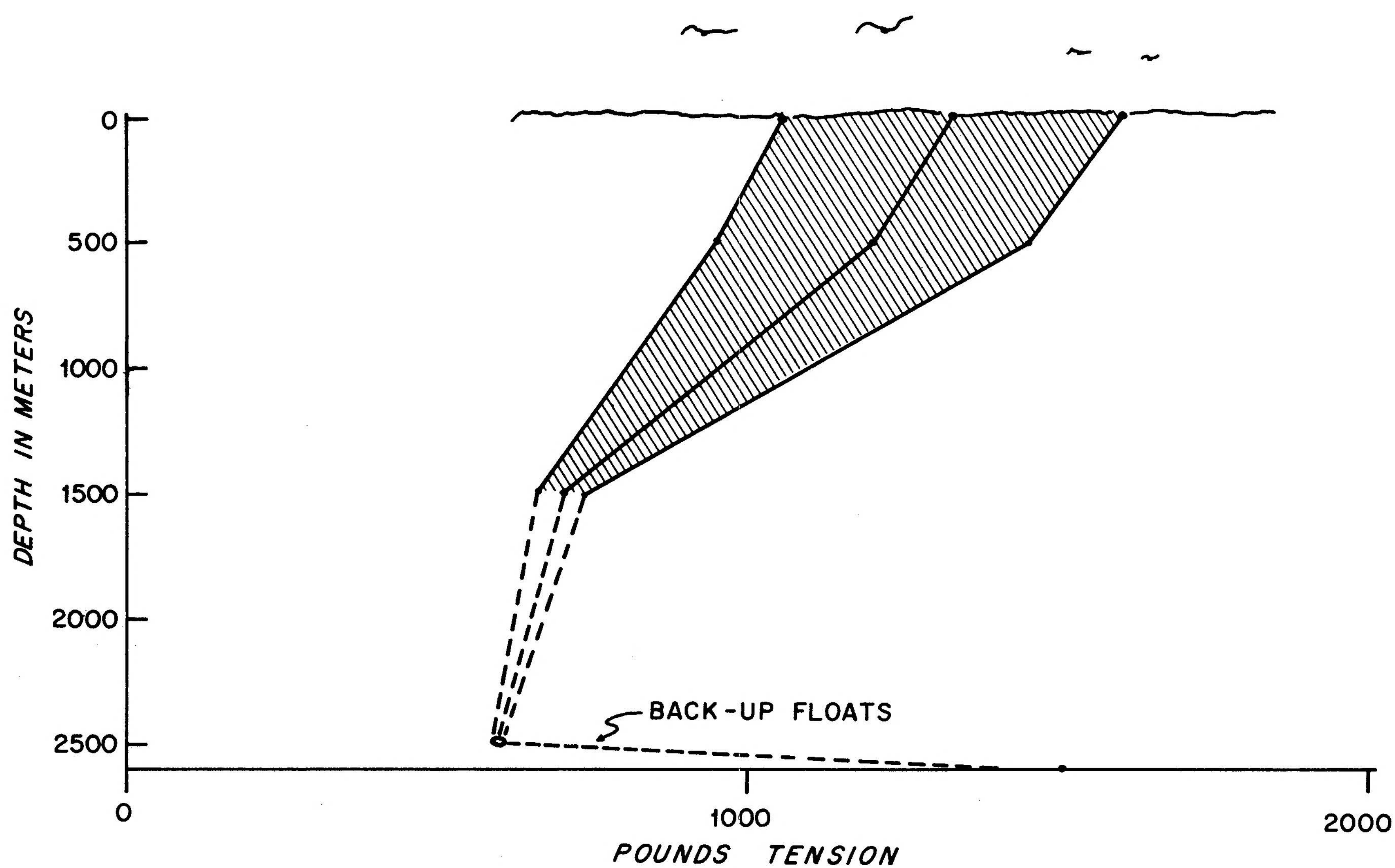


Figure 19. Tension Means and Spread #285

accelerometers. Flutter due to the shedding of Karman vortices should appear in these accelerometer records. Large displacements which may occur due to "dancing" or resonant whipping effects down the mooring line seem to be present in the data. Eight such occurrences were noted during run 1, and 4 during run 2. These are small accelerations as would be expected, however the duration is many seconds. Typical peak acceleration values of 0.3 g with a period of 14 seconds could indicate a resultant displacement of about 100 feet to satisfy this acceleration. These observed accelerations could likewise be produced by an angular translation of the instrument case from the vertical. The phase difference between the two accelerometer signals may be accounted for by case rotation during either mechanism suggested. Both acceleration channels (Figure 18) show these acceleration bumps which occur immediately after anchor release.

The current meter record was inspected to determine whether correspondence existed between case rotations, as seen in the magnetic compass records and these acceleration signals. Each acceleration signal occurred precisely during a 360° rotation of the current meter. The radial acceleration values produced by this rotation alone are not large enough to account for the magnitude observed suggesting that tilt or horizontal displacement accompanied the rotation. The primary purpose of the sensors however, is to detect vibratory motions due to vortex shedding which will produce frequencies somewhat higher than those observed in the phenomena mentioned

A range of Reynolds numbers was calculated for the instrument case for current speeds from 5 to 50 cm/sec, where:

$$R_n = \frac{dV}{\nu}$$

R_n = Reynolds number

d = Diam. of instrument case in ft.

V = current speed (ft/sec)

ν = kinematic viscosity (ft^2/sec)

The kinematic viscosity value was based on an average temperature at 500 meters of 5^{o} C yielding a value of 1.7 x 10^{-5} ft^2/sec. This range of Reynolds numbers permitted an average Strouhal number (0.14) to be determined. From this the frequency of strumming due to Karman vortex shedding was determined as a function of current speed by the following relationship:

$$f = \frac{Sv}{d}$$

where:

f = Karman shedding freq. (cps)

S = Strouhal number

v = current speed (ft/sec)

d = instrument case diam. (ft.)

Reynolds and Strouhal numbers were likewise determined for the mooring line to determine the vortex shedding frequency for a range of expected current values. An average

Strouhal number of 0.2 was used for the mooring wire which was 0.345" in diameter.

Table No. IV lists the frequency of oscillation due to vortex shedding for a range of expected current values. Listed also are the expected range of accelerations to be found for several possible instrument case displacements and mooring line displacements due to this force.

Inspection of Figure No. 18 shows portions of the X and Y acceleration records. Calculated acceleration values for the instrument case due to vortex shedding for the current measured at this time are below system noise, which appears as the predominant signal in the records. Modification to increase the sensitivity, by a factor of five, of the acceleration channels in the instruments have been made for the next test series. Anticipated values of acceleration from the remote acceleration sensors on the wire should be within the present sensitivity range.

Conclusions - An instrument has been designed, constructed and tested at sea to provide an analog record of tension values in a mooring line with accurate timing to permit correlation of these events at different points in the mooring. Also recorded are vibrations induced normal to the instrument case and mooring line due to induced vortices. Acceleration of the instrument in a plane along the instrument (Z axis) may also be recorded to determine the vertical motion due to surface excitation forces.

TABLE NO. IV

Karman Vortice Frequencies and Expected Peak Accelerations

	Current Speed CM/SEC	Reynolds Number $R_n x10^4$	Shedding Frequency fHZ	Peak Acceleration in g's for P. to P. Displacement of		
				3.5"	7"	14"
INSTRUMENT CASE	5	0.58	0.04	.00026	.0005	.001
	10	1.10	0.08	.0012	.0024	.0048
	15	1.67	0.12	.0025	.005	.010
	20	2.20	0.16	.004	.008	.016
	25	2.78	0.20	.007	.014	.028
	30	3.32	0.24	.009	.018	.036
	35	3.74	0.26	.010	.020	.040
	40	4.75	0.31	.016	.032	.064
	45	5.10	0.36	.019	.038	.076
	50	5.45	0.38	.023	.046	.092
&	CM/SEC	$R_n 10^3$	fHZ	0.17"	0.34"	0.68"
MOORING WIRE	5	0.29	1.18	.009	.02	.04
	10	0.54	2.22	.04	.08	.16
	15	0.83	3.4	.09	.20	.40
	20	1.1	4.5	.16	.32	.64
	25	1.4	5.7	.24	.50	1.0
	30	1.6	6.8	.40	.80	1.6
	35	1.9	7.65	.50	1.0	2.0
	40	2.2	9.0	.70	1.4	3.0
	45	2.5	10.5	.90	1.7	3.4
	50	2.7	11	1.0	2.0	4.0

2. Testing and Evaluation of Mooring Line Components

In order to evaluate the characteristics and the performance of mooring line components a comprehensive series of tests was outlined (Ref. No. 2) and performed in 1968. These tests were conducted at sea and in land testing facilities.

Purpose of tests, experimental phase, and evaluation of results of these sea and land tests are hereafter reviewed.

2.1 Experiments conducted at sea

The experimental program of evaluation in the sea environment was conducted at three different locations. One, site "D" (39° 00N 70° 00W), was a deep water ocean test site (2600 meters depth), the other the "Buoy Farm" (41° 18' N 71°01'W) was a shallow water offshore test site (40 meters depth). A special mooring was set in intermediate depths for visual inspection by the Institution's deep submersible ALVIN.

2.1.1 Long Term Deep Sea Moorings

Purpose of tests - The purpose of these tests was to evaluate in situ and for relatively long periods of time, the design and the selection of the components of full scale experimental buoy systems. Improved wire rope configurations and smaller scope suggested by past experience (Ref. No. 1) were incorporated in these systems. The performance of wire ropes of various degrees of flexibility and strength was to be established. To complement the empirical evaluation, the environmental forcing functions and mooring response were to be measured and recorded at several points in the line.

Experimental Phase - Four long term experimental buoy systems were set at site "D" in 1968. These systems were successfully retrieved after approximately two months on station.

Each of these systems consisted of a surface buoy, a compound (wire and synthetic rope) and taut mooring line, and a back-up "in line flotation" recovery system (Ref. No. 4). The upper 1500 meters of each of the mooring line used wired rope or strand assemblies. These assemblies were made of galvanized steel wires stranded in torque balanced constructions covered with a plastic jacket and terminated at both ends with a swaged fitting and a vibration damping boot (See Figure 20).

The lower part of the mooring line consisted of plaited nylon assemblies - their designed unstretched length was less than the difference between the water depth and the length of the metallic components of the mooring line in order to provide the initial tension characteristic of taut buoy systems. (See Appendix No. 5.2. Formula for computing the length of synthetic fiber components in a taut mooring line.) The surface buoy was equipped with a wind recorder. Instruments for measuring and recording current and tension were inserted in the mooring line between wire rope or nylon rope assemblies. The exact configuration of each of these systems is depicted in Figures No. 21, 22, 23 and 24. Date of setting, number of days on station, size and type of mooring line rope, elongation, weather conditions and test results are presented in Table No. V: 1968 Long Term Engineering Surface Moorings, Summary of Performance.

Evaluation of Results - The careful design and preparation of these experimental buoy systems and the expert handling during deployment resulted in the complete recovery of all components and test data.

Long term tension values, distributed from buoy to anchor, were obtained for the first time. their analysis, as already discussed, yielded interesting and important engineering information constantly

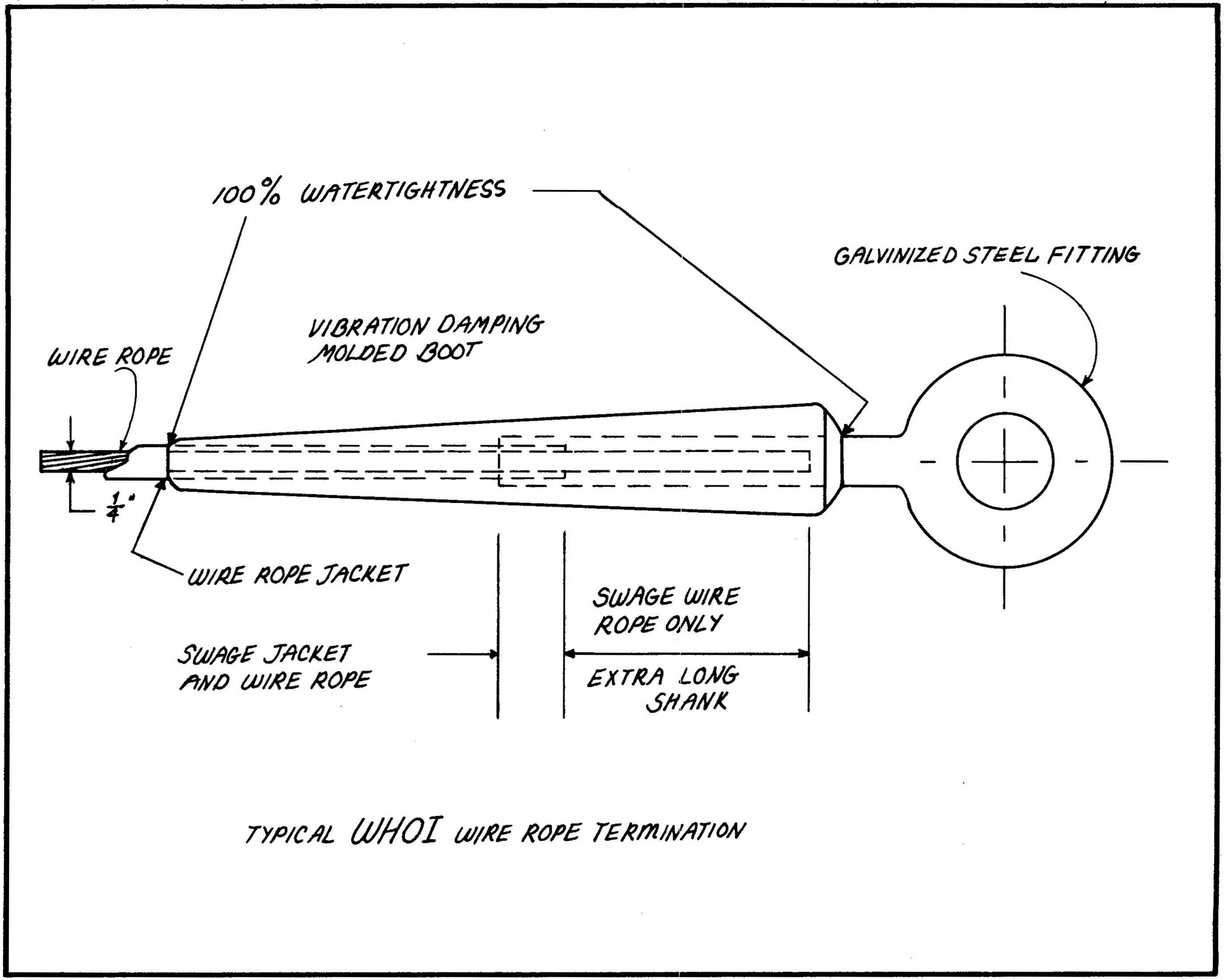


Figure 20. Typical W.H.O.I. Wire Rope Termination

PURPOSE OF TEST = EVALUATION OF MOORING CONFIGURATION AS SHOWN OVER A TWO MONTHS PERIOD. MEASUREMENTS OF MOORING TENSION

PROCEDURE = USUAL BUOY FIRST LAUNCHING. CHECK PROPER ANCHORING & FUNCTIONING OF SURFACE INSTRUMENTATION. STRETCH 7%

EQUIPMENT = AS SHOWN

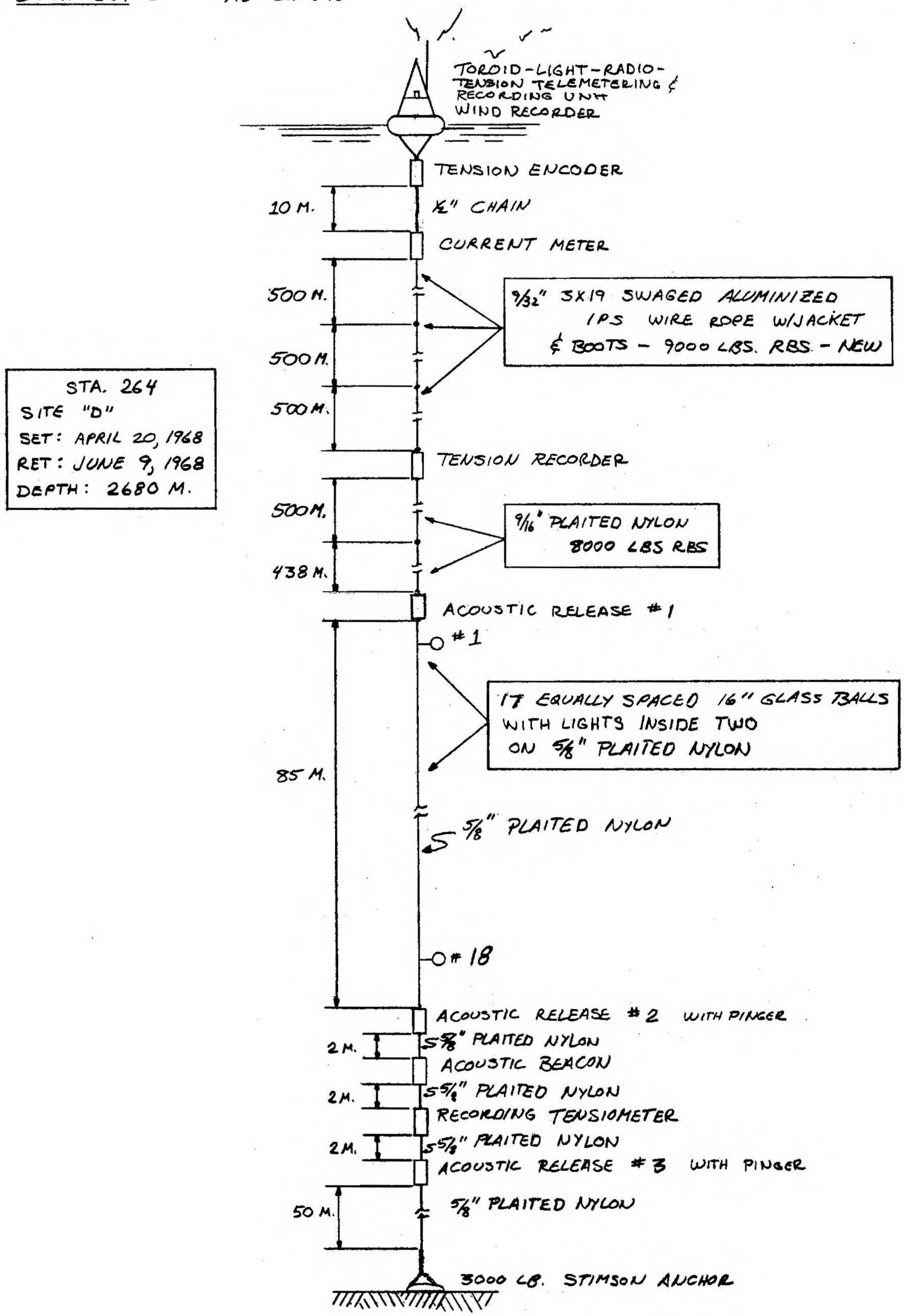


Figure 21-24. Station 264, 269, 275, 279 Long Term Engineering Moorings

PURPOSE OF TEST = EVALUATION OF MOORING CONFIGURATION AS SHOWN OVER A TWO MONTH PERIOD. MEASUREMENTS OF MOORING TENSIONS

EQUIPMENT = AS SHOWN

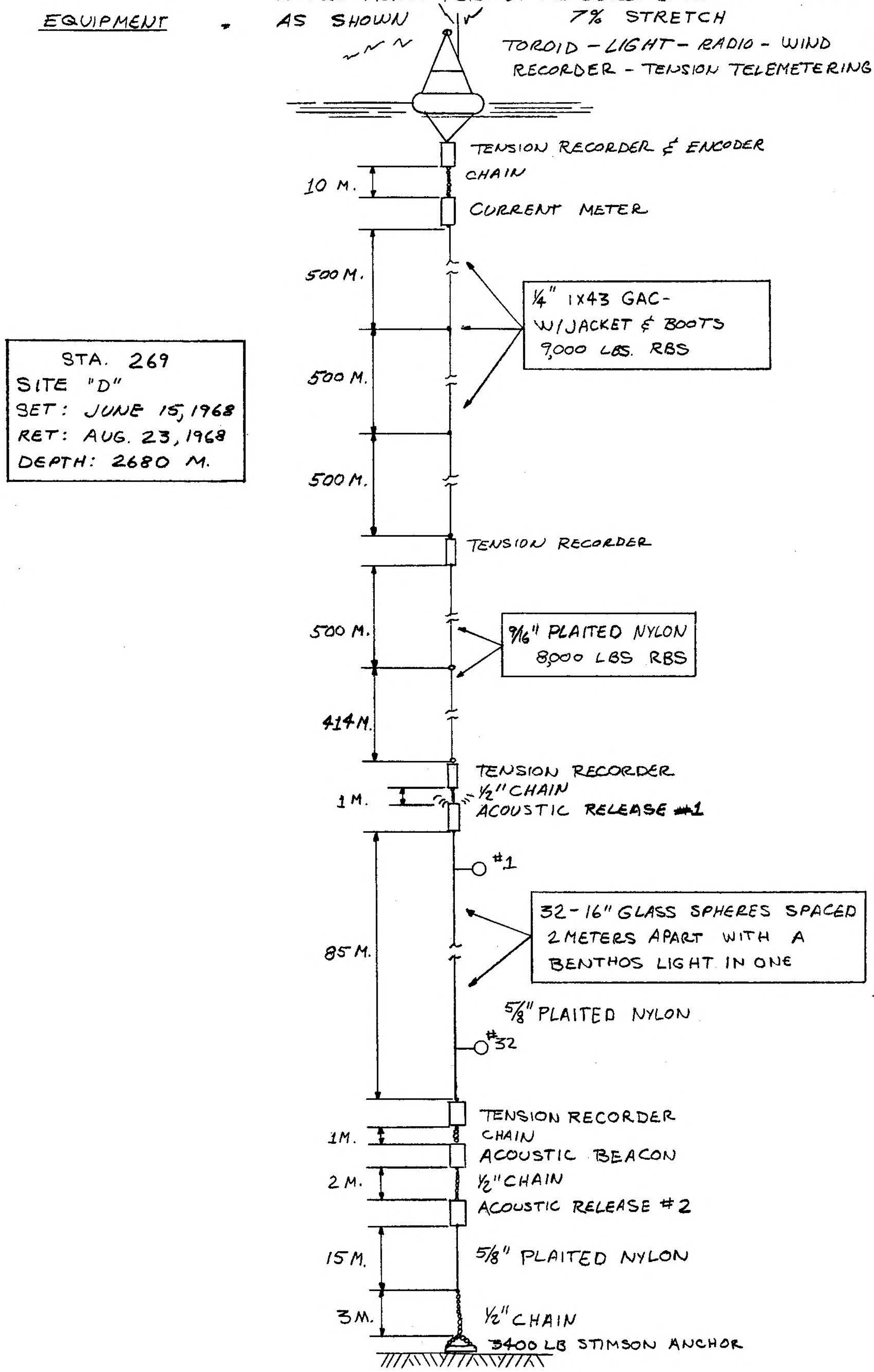


Figure 22

PURPOSE OF TEST — EVALUATION OF MOORING CONFIGURATION AS SHOWN OVER A TWO (2) MONTHS PERIOD - MEASUREMENT OF MOORING TENSION STRETCH 12%

EQUIPMENT — AS SHOWN

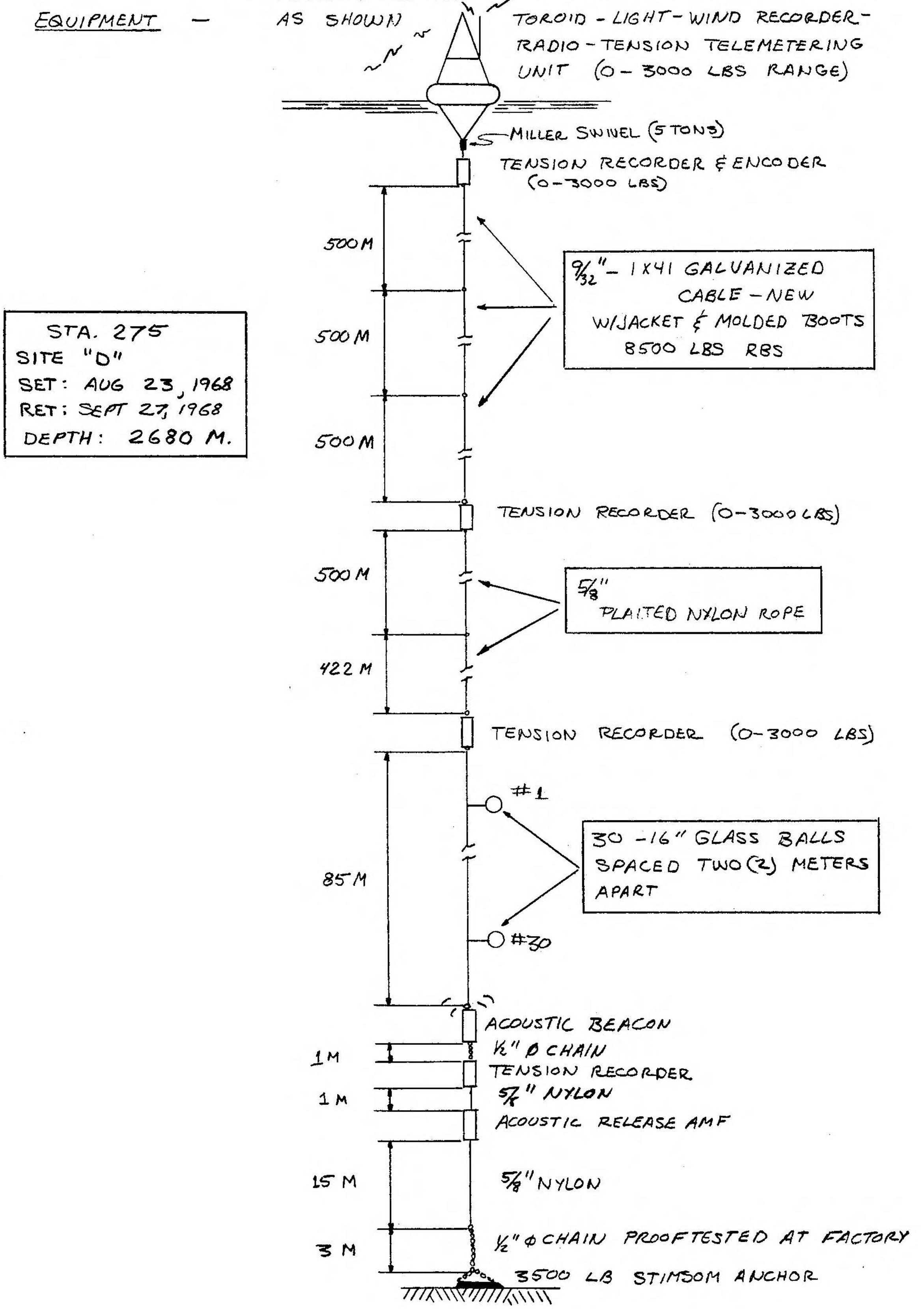


Figure 23

PURPOSE OF TEST — EVALUATION OF MOORING CONFIGURATION AS SHOWN OVER A TWO MONTH PERIOD - MEASUREMENT OF MOORING TENSION STRETCH 13%

PROCEDURE — LAUNCH BUOY, PAY OUT MOORING LINE, ATTACH BALLS, LAUNCH ANCHOR, CHECK ANCHORING, RETRIEVE NEXT CRUISE

EQUIPMENT — AS SHOWN

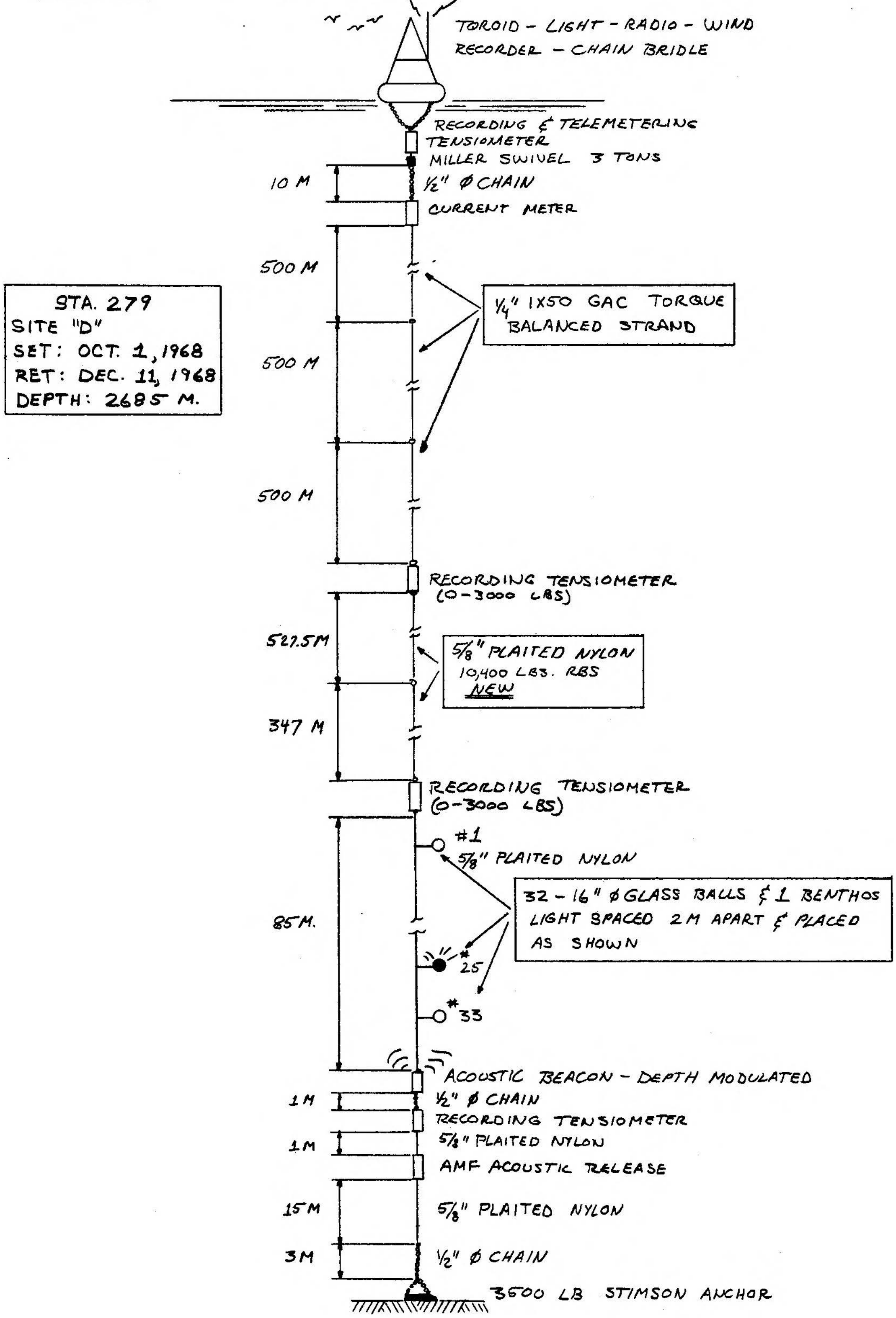


Figure 24

TABLE NO. V

1968 LONG TERM ENGINEERING SURFACE MOORINGS, SUMMARY OF PERFORMANCE

(ALL MOORINGS SET AT SITE D 39°N 70°W)

Sta. No.	Cruise	Date Set	Date Retrieved	No. of Days on Station	Size & Type of Wire Rope	Size & Type of Nylon Rope	Nylon Elongation	Weather	Inspection & Tension Testing of Retrieved Components
264	April	April 20 1968	June 9 1968	64	9/32" 3x19 Swaged Aluminized IPS w/Jacket & Boots 9,900 lbs UBS	9/16" Plaited	7% ?	Severe Weather While on Station	Boots Leaked No Corrosion No Strength Reduction
269	June	June 15 1968	August 23 1968	70	¼" 1x42 Galv. IPS w/Jacket & Boots 10,880 lbs UBS	9/16" Plaited	7% ?	Average Weather While on Station	No Corrosion No Strength Reduction
275	August	August 23 1968	September 27 1968	36	9/32" 1x41 Galv. IPS w/Jacket & Boots 9,940 UBS	5/8" Plaited	12% ?	Average Weather While on Station	Boot Leaked No Appreciable Corrosion No Jacket Ruptures No Strength Reduction
279	October	October 6 1968	December 12 1968	68	¼" 1x50 Galv. IPS w/jacket & Boots 10,100 lbs UBS	5/8" Plaited	18% ?	Hurricane Conditions While on Station (Hurricane Gladys)	Kinks at 750 m- Boots Leaked w/some corrosion Strength Reduc. @ Damaged Area only.

used in updating the design of new compound moorings. Furthermore the visual inspection and laboratory testing of the retrieved components confirmed the fact that corrosion and fatigue play a minor role in the deterioration process of the mooring line wire ropes as long as they were exempt of severe mechanical damage. Torque balanced strands despite their lesser propensity to kink formation are not immune to such damage, as can be seen from Figures No. 25 and 26. This badly twisted section of the mooring line of station No. 279 was 750 meters below the surface. Station No. 279 was set with a high percentage of nylon stretch (18% actual) and survived extremely severe surface conditions (hurricane Gladys). The cause of the damage which could have occurred during launch, or on station, or upon retrieval could not be identified.

Most of the wire rope terminations used were in "like new" condition. No severe deterioration of the galvanized steel hardware (chain, shackle, links) could be detected.

The limits of this successful but small testing effort should be recognized. The significance of the results obtained from a small number of experiments is always questionable. Furthermore, test conditions varied markedly from one station to the other. Some were implanted in moderate weather (Stations No. 269 and No. 275) whereas others had to resist storms of hurricane force (Stations No. 264 and 279). Different values of mooring compliance introduced by unsuspected errors in nylon length measurements further add to the difficulty of formulating a comparison. Their merit of a flexible wire rope versus a stiff strand and the advantages of a taut moor versus a relatively slack configuration need to be studied.

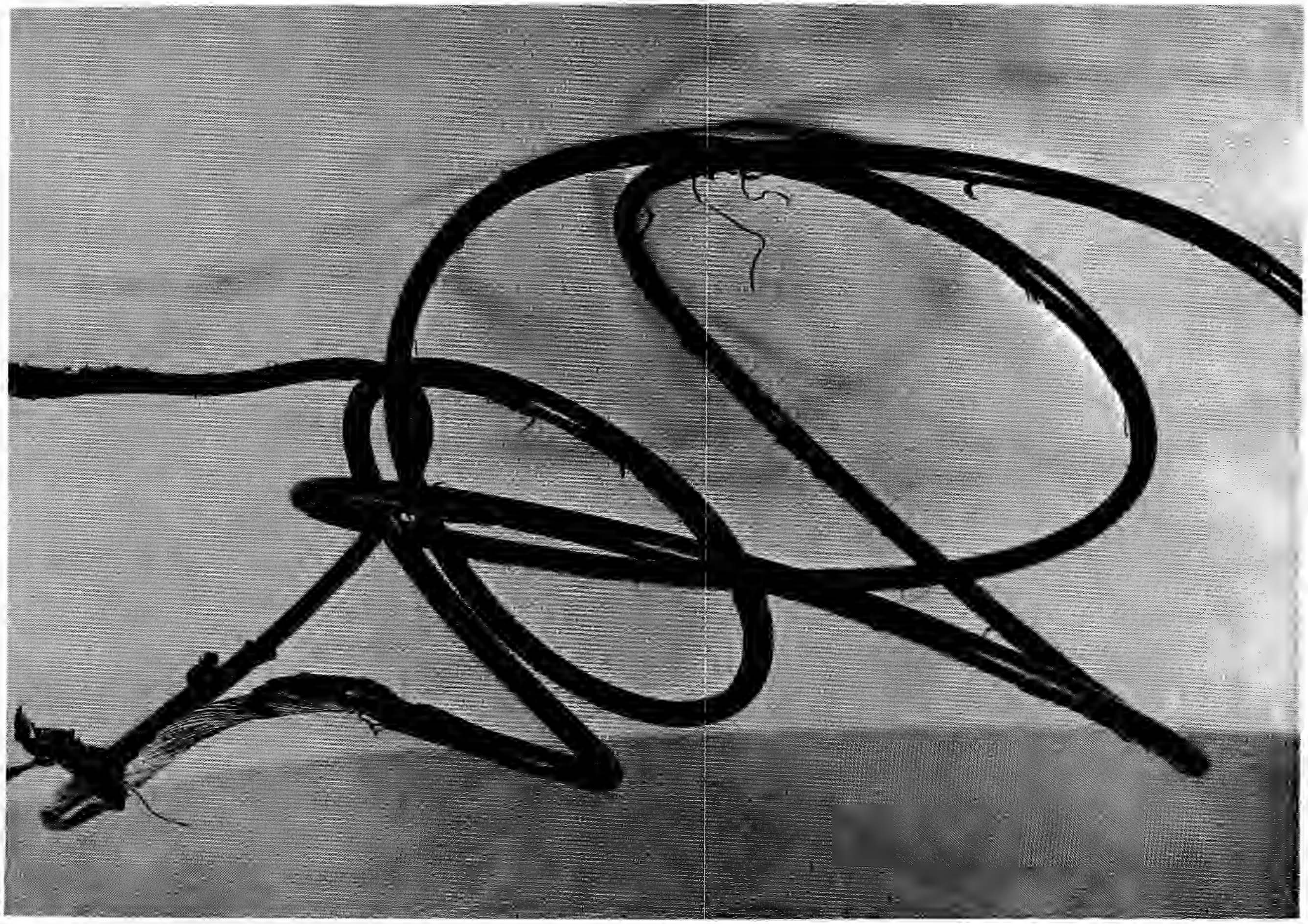


Figure 25. Damaged Wire Rope of Station 279

Figure 26. Closeup of Damaged Section

2.1.2 ALVIN Experimental Mooring

A mooring was implanted at 39° 52.3'N and 69° 12.8'W on September 25, 1968 to be observed and inspected by the W.H.O.I. deep submersible ALVIN. The mooring was placed at a water depth of 1512 meters, well within the operating capability of the craft.

Objectives

The objective of the experiment was to determine if a deep submersible could inspect and monitor a deep sea mooring. Specifically, it was desired to evaluate the capability of ALVIN to:

- hover downstream and alongside the mooring within photographic range,
- minimize motion in the X,Y and Z planes in the presence of currents less than one knot,
- film specific reference marks on the cable,
- observe and measure the mooring line angle as a function of depth and the horizontal and vertical motions including vibration of strumming,
- generally inspect the mooring line looking for damage and kinks,
- observe and catalog biological visitors with an interest in the mooring,
- observe the motions of a current meter suspended in the mooring,
- observe attitude and penetration of a Stimson anchor,
- look for the unexpected.

The Mooring

Figure 27 shows a detailed configuration of the mooring. A toroid surface buoy with light was used. A tensiometer was installed

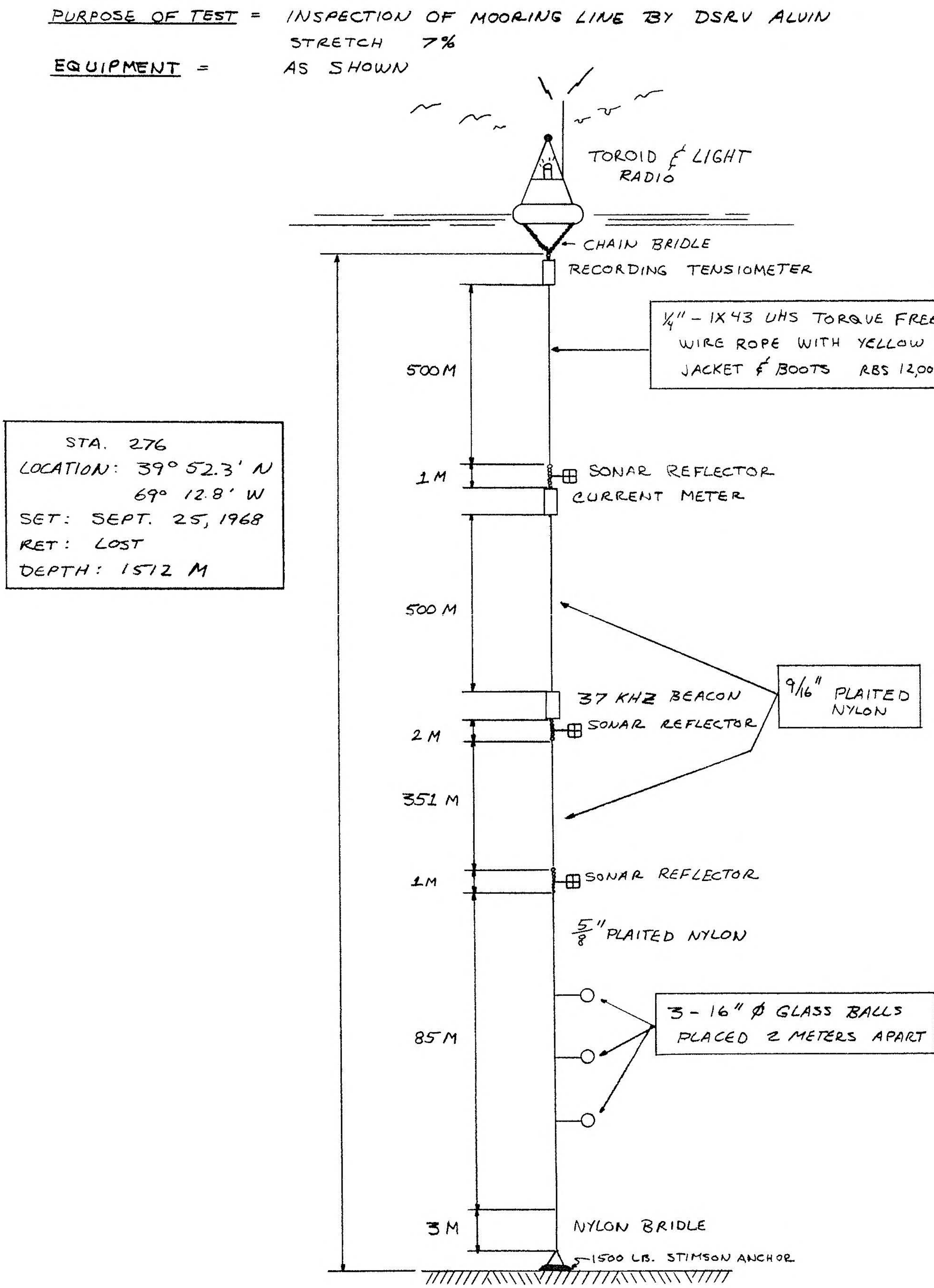


Figure 27. ALVIN Inspection Mooring

immediately below the buoy to record the mooring tension during the dive period. The first 500 meters of the mooring line were made of ¼" 1x43 torque-free, ultra high strength jacketed strand rated 12,000 pounds RBS. The jacket was bright yellow for better underwater visibility. A dummy current meter was suspended below the wire, followed by 9/16" plaited nylon for the remainder of the mooring. Sonar reflectors at 500, 1000 and 1350 meters and a 37 KHz pinger at 1000 meters were installed to aid the submersible in locating and following the mooring line. Three 16" glass spheres installed above the anchor served as additional sonar targets. A special nylon bridle was used at the anchor to permit cutting by the submersible in the event of entanglement.

The Operation

On October 16 ALVIN was launched to begin the first dive for inspection of the mooring. After submerging to a depth of 22 meters trouble developed in the lighting of the motion picture system. Inasmuch as filming was an important part of the dive it was decided to effect repairs before proceeding. During this shallow dive the mooring cable attached to the buoy was quite visible. The submersible was brought back aboard the tender and repairs to the lights made and another dive started. While lowering ALVIN the two forward elevator cables snapped and the submersible pitched into the water with the crew and observer aboard and the hatch open. The personnel escaped, the pressure hull flooded and ALVIN sank to the bottom.

The buoy was used as a marker for the subsequent search effort for the submerisble. On October 22, 1968, the U.S. Coast Guard reported the buoy missing. On or about November 20, 1968 a passing vessel (Tanker Benoil) picked up the surface buoy with the tension recorder still intact, approximately 100 miles south of its' original position. The tower was missing and one third of the toroid was cut away. (See Figure 28). The shape of the cut and the abrupt increase of tension beyond full scale (>3000 pounds) noted on the record, clearly indicate that the buoy was run down by a vessel and was caught in her screws. The tension record shows that the collision occurred at 0300 on October 21, 1968.

2.1.3 Deep Environment Wire Rope Test

A bottom mooring was set at the ALVIN test mooring site to evaluate the deterioration of various ropes under tension (1000 pounds) in a deep ocean environment. The objective of the experiment was to place these test specimens in a known location using a deep submersible and to return to that location in nine (9) months to a year and retrieve the samples for inspection. Figure 29 shows the test rack, float and sonar reflector which was installed. A photograph of the test rack assembly is shown in Figure 30. It is anticipated that the test rack will be recovered during the ALVIN salvage operations.

Samples mounted in the rack were:

1. (1) ¼" 1x43 Torque balanced UHS bare, galvanized with galvanized swaged fittings
2. (1) ¼" 1x43 Torque balanced UHS w/jacket, boots and galvanized swaged fittings
3. (1) Same as 2. except with cuts in the jacket
4. (1) 5/16" 3x19 Torque balanced galvanized rope, bare w/swaged fittings

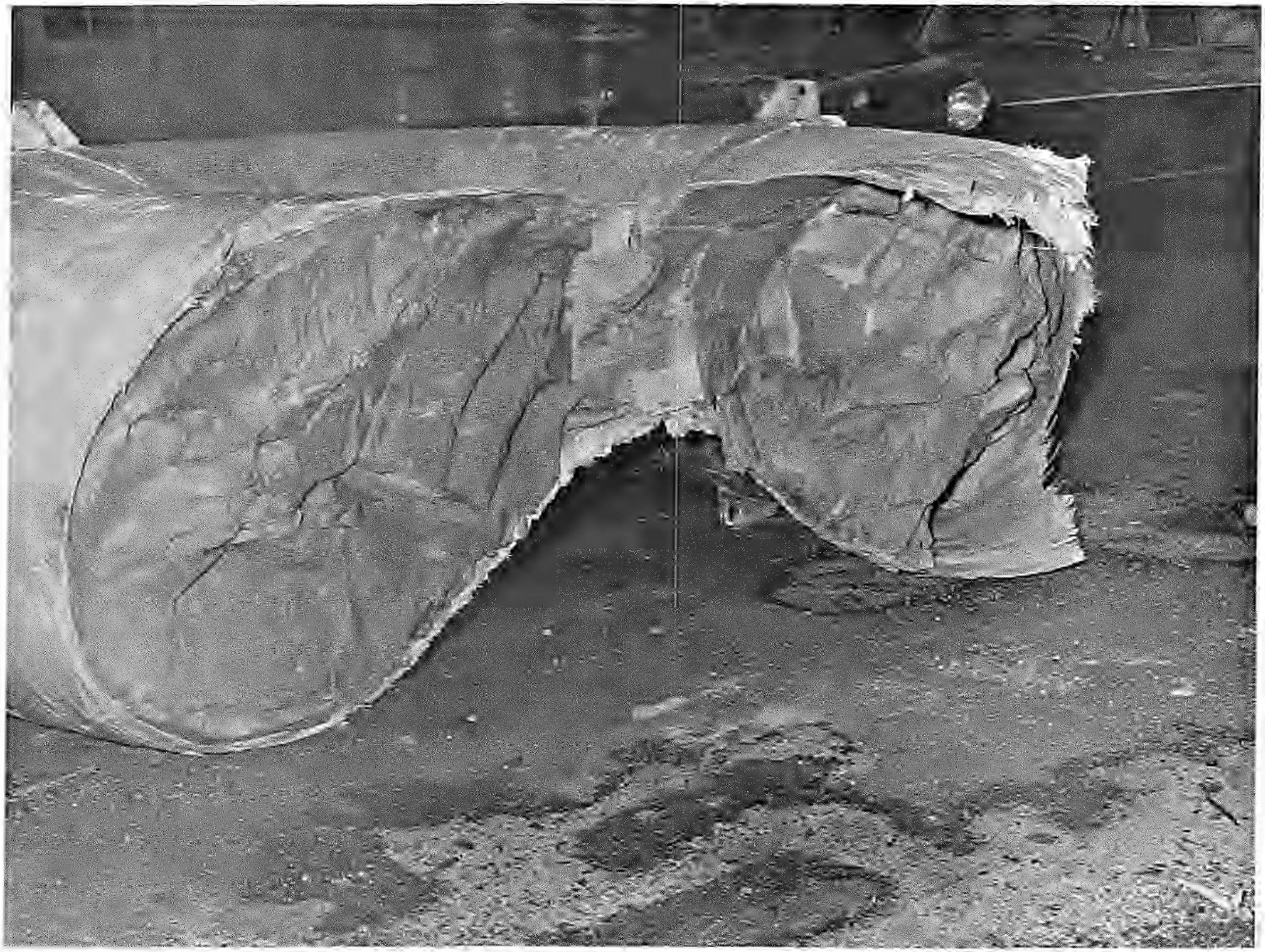


Figure 28. ALVIN Inspection Mooring Buoy After Recovery

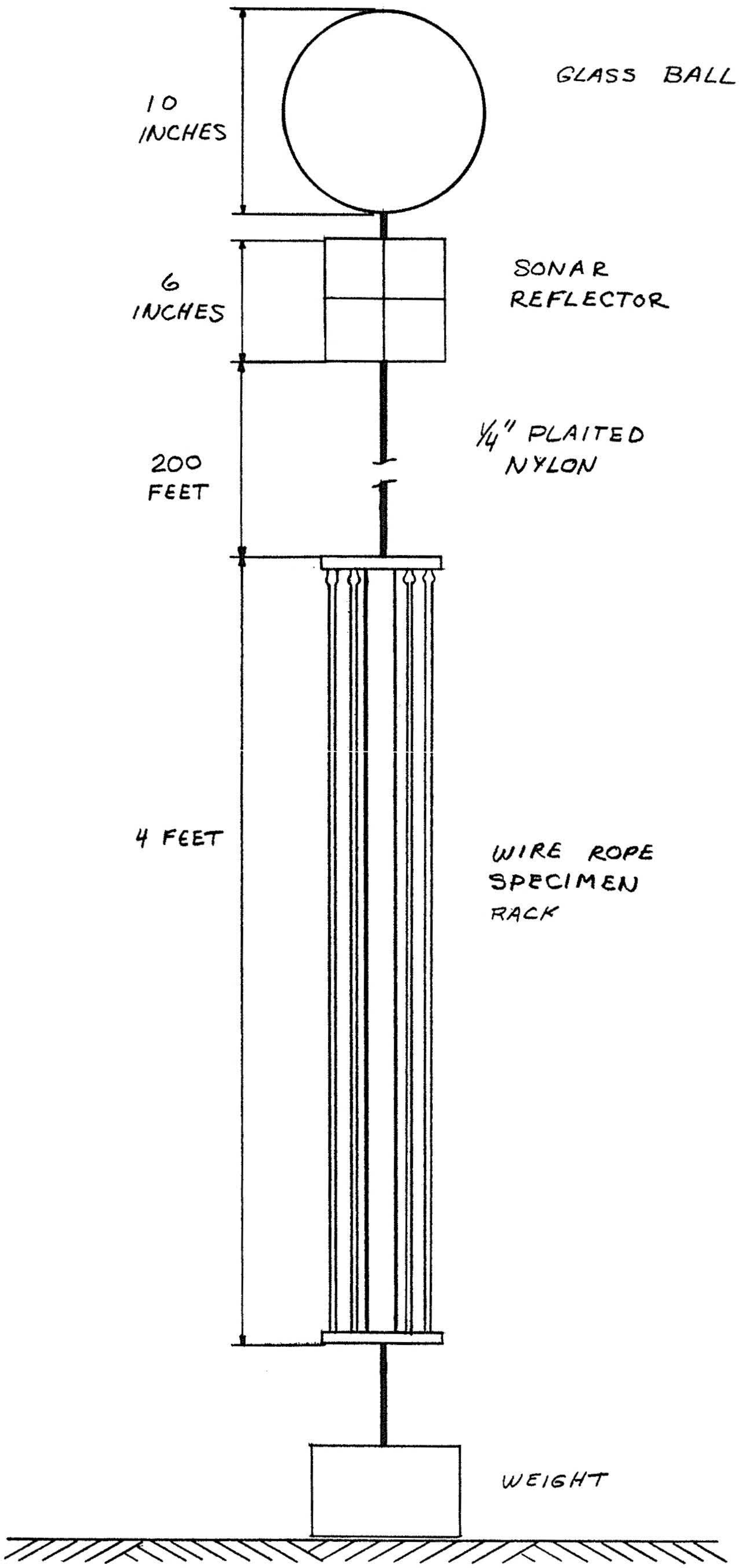


Figure 29. Deep Environmental Cable Test Mooring

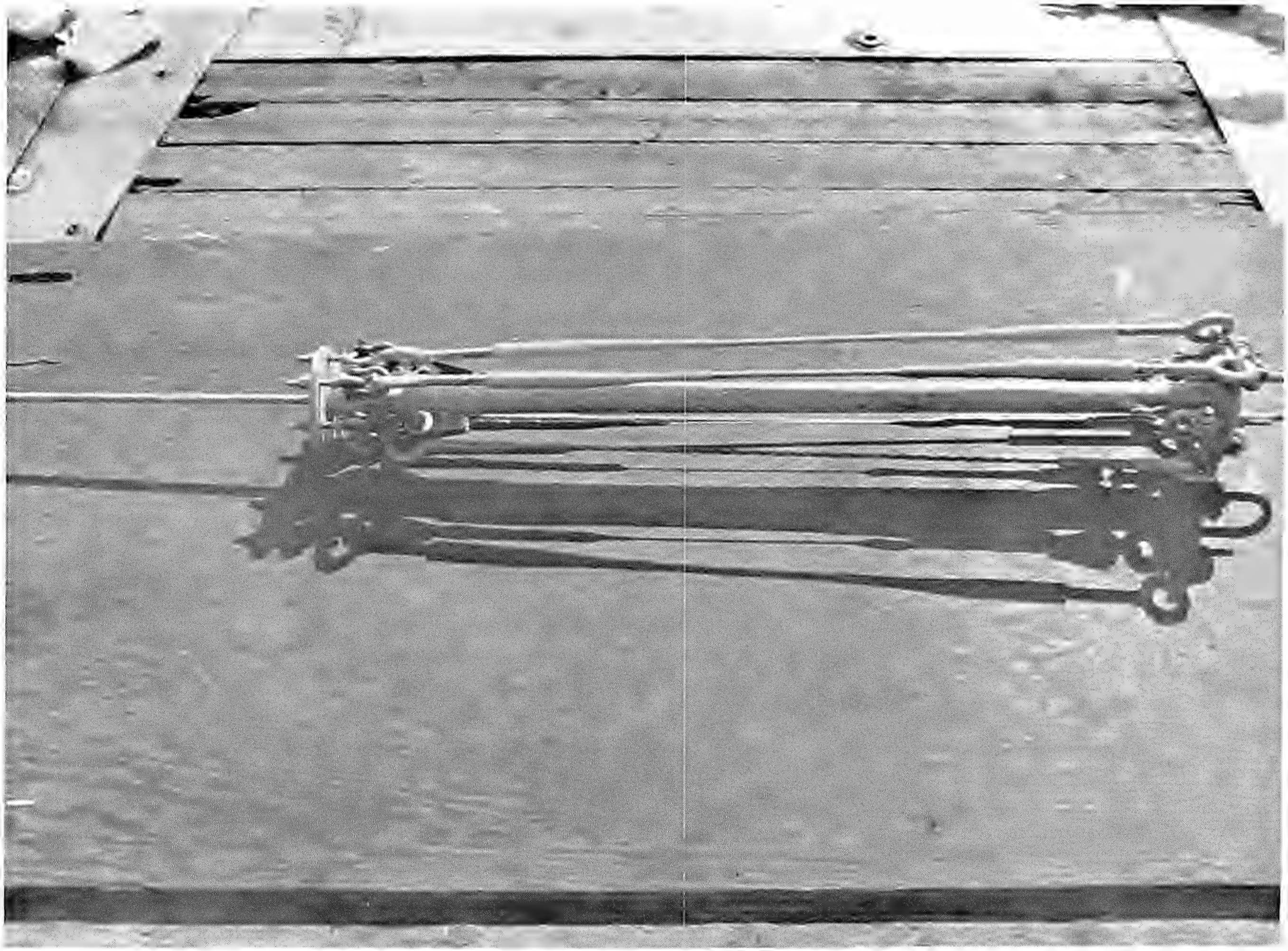


Figure 30. Deep Environmental Cable Test Rack

5. (1) Monofilament Inconel 625 bare with plastic thimbles and nicopress fittings
6. (1) Monofilament, Titanium, bare with plastic thimbles and nicopress fittings.

2.1.4 Shallow Water Tests

Purpose of tests - The purpose of these tests was to evaluate the performance and eventually establish the endurance limit of various samples of mooring line components (wire rope, chain, hardware) submitted to similar loading and environmental conditions. A figure of merit could thus be obtained on which to base, in part at least, the selection of components for deep sea mooring applications.

A test site in shallow but open waters and proximate to Woods Hole was selcted. In this way cost and effort in the deployment, inspection, and retrieval of the samples could be minimized and yet the environmental conditions could be kept severe.

The test was designed to provide a fair approximation of the loads encountered in deep sea moorings and the test sequence was arranged to insure a simultaneous loading of the samples tested.

Experimental Phase

Test Site - The test site was established with the approval of the Coast Guard authorities at 41°18'N and 71°01'W, approximately seven miles southwest of Cuttyhunk, Mass. The average depth of the water is 125 feet.

Test Array - Twenty moorings set in a rectangular pattern constituted the test array. The four corner buoys were equipped with tower and lights and were moored on chain only for navigational safety

purposes. The sixteen other moorings consisted of a surface float, a 25 meter wire rope sample, a 1000 lb. weight, a length of ½" chain, a length of 1½" chain and a 1500 lb. Stimson anchor.
In this manner the tension on the samples was approximately equal to the average tension at the buoy of a deep sea compound mooring set at station "D". Figure No. 31 shows a typical corner mooring and a typical test mooring.

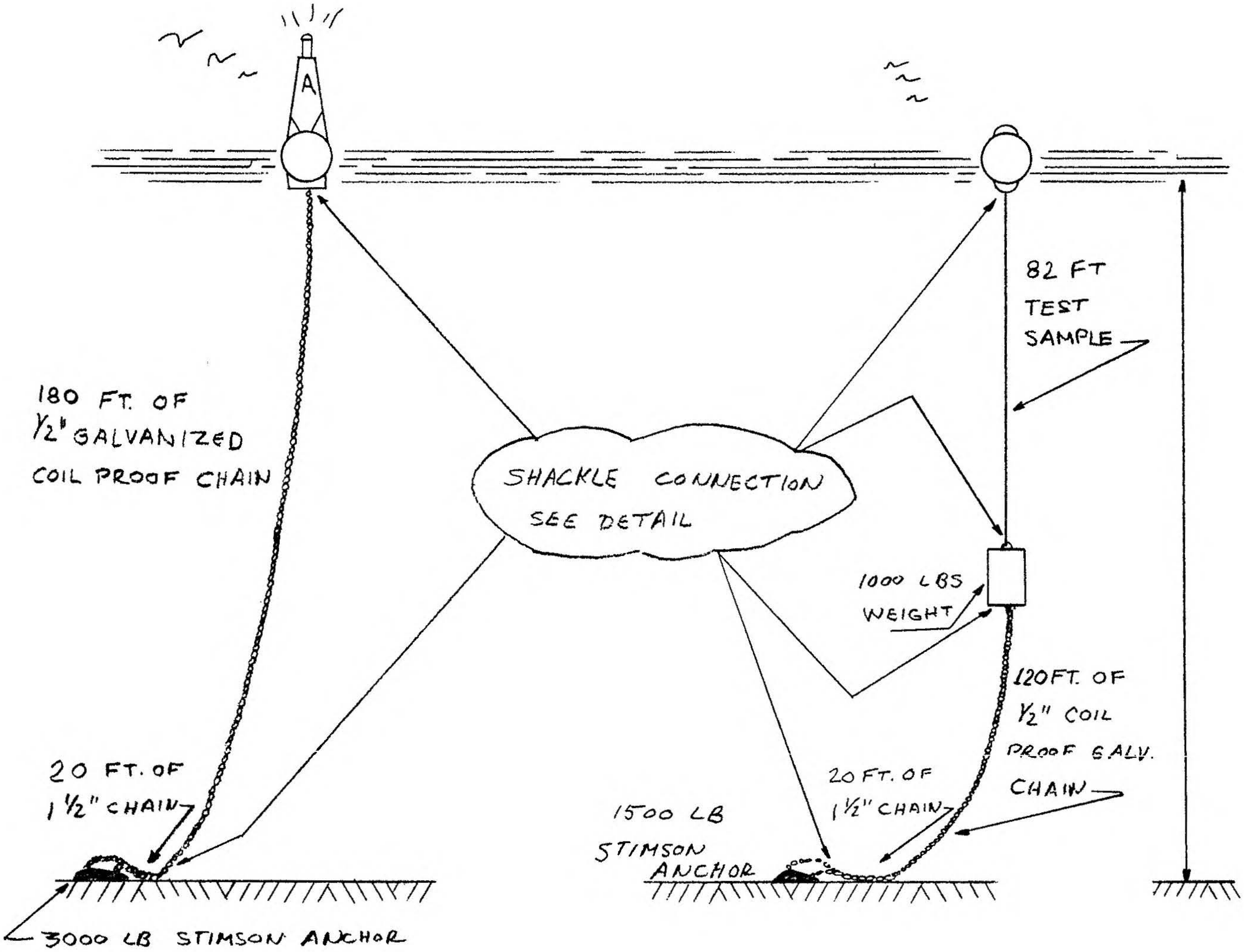
Wire Rope Samples - Two samples each of eight different types of wire rope were placed for evaluation. Fourteen samples were protected against corrosion by wire coating and plastic jacket over the rope in an attempt to limit the number of deterioration factors influencing their endurance. Two samples were of bare Inconel 625. The description of the samples and their location in the array is as shown in Figure No. 32.

History - An instrumented pilot mooring was set March 15, 1968 and retrieved April 3, 1968. The tension record showed severe dynamic loading due to storm action (from 500 lbs. to 1500 lbs.).

Soon after other moorings were set and by April 12, 1968 twenty buoys with their identification markings were set in a grid pattern and the shallow water tests started. (Figure No. 33).

The first failure was reported the 29th of April 1968, Buoy 0-1, which was stranded near Gay Head. Retrieval of this buoy and its attachment including the parts left on the site floor revealed the cause of the failure: a shackle linking the weight to the chain had lost its pin. Buoy 0-1 was immediately replaced with all shackles welded prior to deployment.

The array, by then known as the "Buoy Farm", was regularly checked by flights of the Institution's airplane. On two occasions the moorings were inspected by divers who could not detect any sign of deterioration.



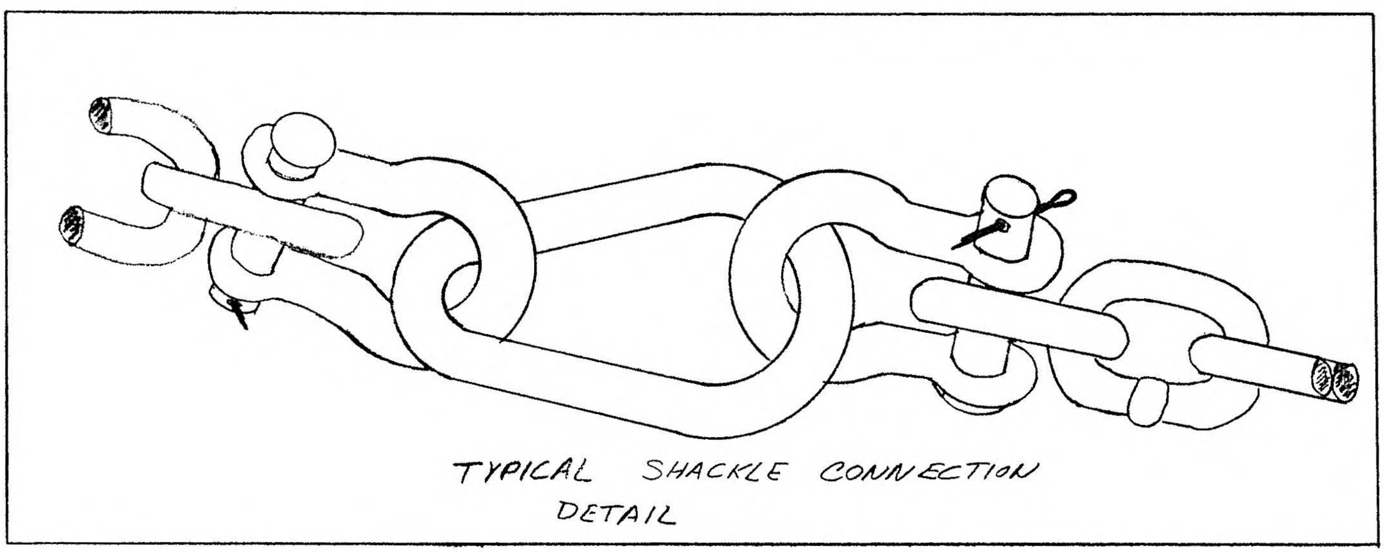
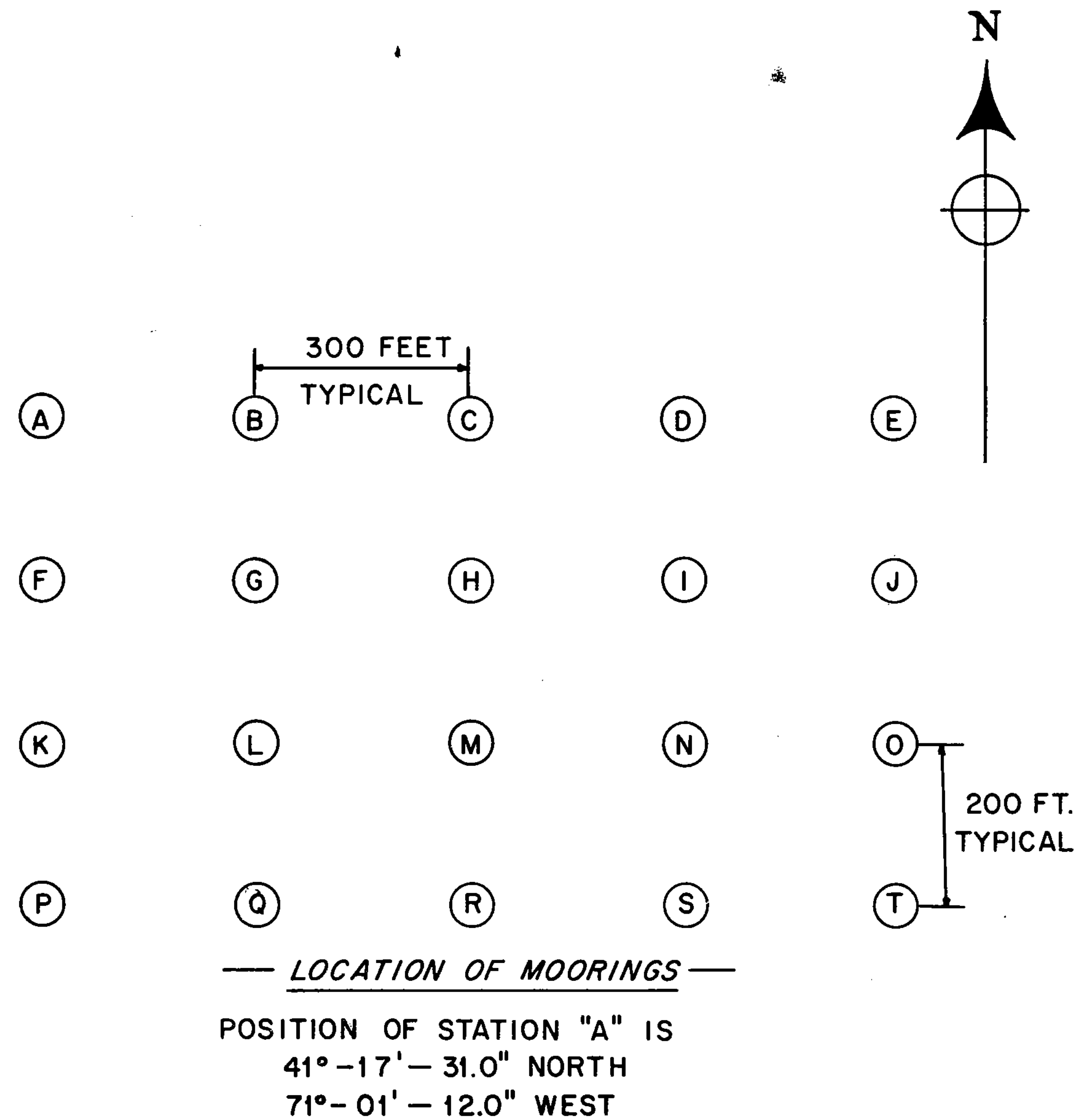


Figure 31. Typical Moorings. Shallow Water Array



STATION	WIRE ROPE SAMPLE	LBS RATED BREAKING STRENGTH	DATE SAMPLE SET	DATE SAMPLE RETRIEVED
A	NONE		April 3, 1968	Jan. 29, 1969
B	¼" 1x19 GAC	7,000	April 8, 1968	Jan. 29, 1969
C	¼" 1x19 GAC	8,200	April 9, 1968	--
D	¼" 1x19 GAC	8,200	April 10, 1968	Jan. 29, 1969
E	NONE	--	April 11, 1968	Jan. 30, 1969
F	¼" 7x19 GAC	7,000	April 8, 1968	Nov. 21, 1968
G	¼" 1x19 UHS	13,000	April 9, 1968	--
H	¼" 1x19 UHS	13.000	April 10, 1968	Aug. 12, 1968
I	¼" 1x43 GAC	8,000	April 10, 1968	Jan. 29, 1969
J	¼" 1x43 GAC	8,000	April 12, 1968	--
K	9/32" 3x9 Swaged-Alum.	9,000	April 8, 1968	Nov. 20, 1968
L	¼" 7x19 GAC	7,000	April 9, 1968	--
M	¼" 7x19 Inconel 625	8,200	April 10, 1968	Jan. 29, 1969
N	¼" 1x19 GAC	8,200	April 11, 1968	--
O	¼" 7x19 GAC	7,000	April 12, 1968	Sept. 24, 1968
P	NONE	--	April 3, 1968	Jan. 30, 1969
Q	9/32" 3x19 Swaged-Alum.	9,000	April 9, 1968	July 13, 1968
R	¼" 1x19 GAC	6,500	April 10, 1968	Jan. 30, 1969
S	¼" 7x19 Inconel 625	6,500	April 11, 1968	Oct. 17, 1968
T	NONE	--	April 11, 1968	Jan. 30, 1969

ALL SAMPLES TO BE JACKETED EXCEPT "M" & "S"
ALL SAMPLES TO HAVE 1000 LB WEIGHT ATTACHED

Figure 32. Distribution of Samples. Shallow Water Array

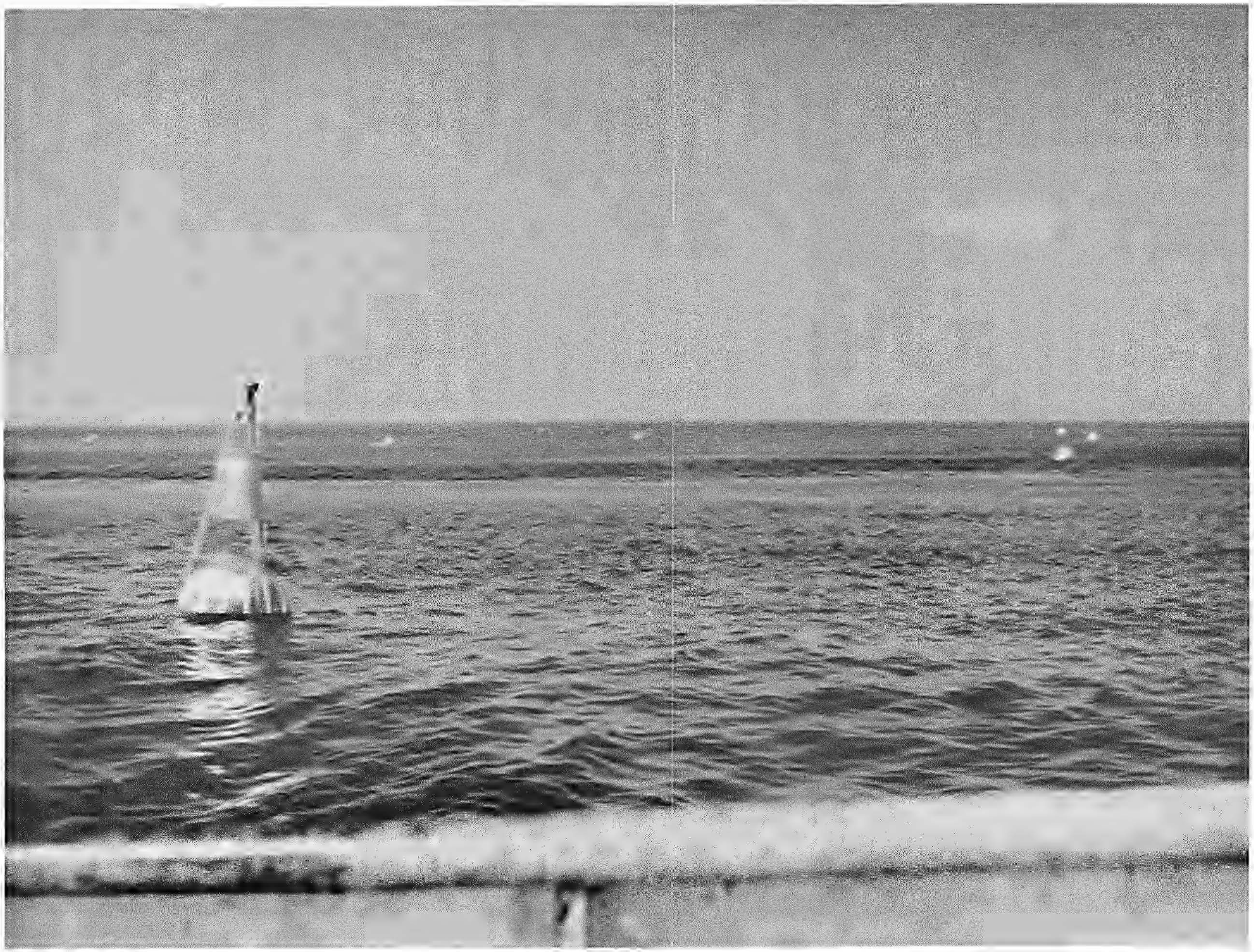


Figure 33. Buoy Farm

On August 19, 1968 another buoy went adrift, and from then until the completion of the test (January 30, 1969) a total of ten test buoys failed. So far, two buoys have been found on beaches (Montauk Point, Martha's Vineyard) and four have been picked up by passing ships. All of the ground tackle (chain and anchors) and most of the buoys and wire rope samples have been retrieved. The performance of each mooring set is further detailed in Appendix No. 5.3: "1968 Shallow Water Test. Control Chart."

Evaluation of results - All failed moorings were retrieved by dragging. In each case the location of the bitter end coincided with the location of a shackle in the line. Samples of wire rope did not fail, and in general were found in good condition, despite considerable marine growth and fouling (See Figure No. 34).

The information gained from the first phase of the shallow water testing can be summarized as follows:

Wire Rope. The evaluation of the endurance limit and the comparison of the performance of the jacketed steel wire rope samples have not been achieved. Pull tests performed on the retrieved samples could not reveal an appreciable reduction of strength. Visual inspection could not detect broken wires or fish hooks.

The polyethylene jacket was slightly damaged in some samples. At the place of damage the zinc coating had prevented the corrosion of the wires. Under undamaged sections of the jacket the wires were found shiny and in "like new" condition.

These findings seem to indicate that when protected by a polyethylene jacket and if not submitted to detrimental handling resulting in loop formation and kinks, coated steel wire ropes loaded to approximately 15% of breaking strength may last a long time (some have been on station 300 days and rode through many storms).

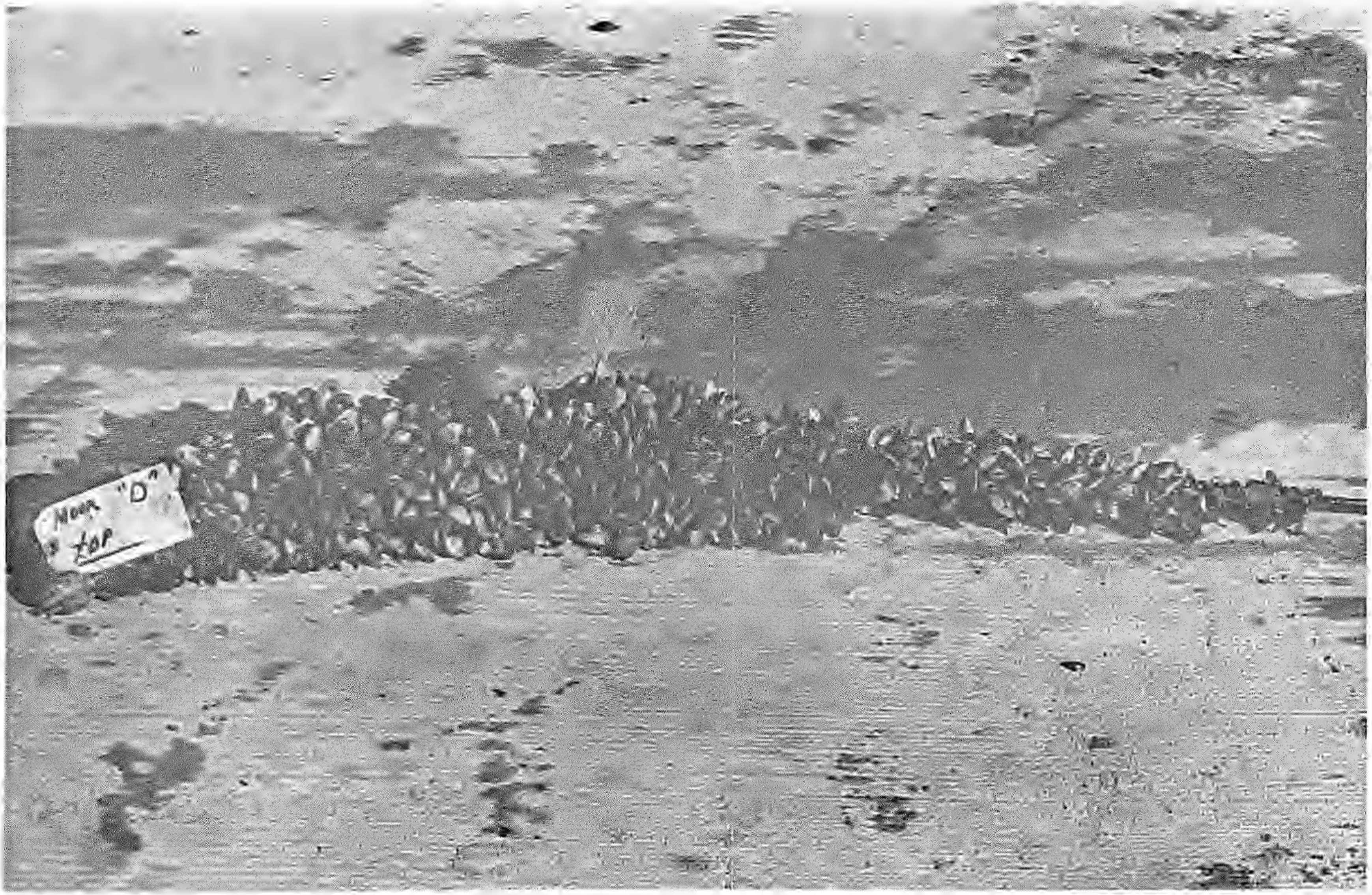


Figure 34. Growth on Wire Rope Sample

Under such conditions, one year of use could be anticipated. This in itself is an interesting result, the service life of these moorings being a total unknown at the beginning of the tests.

The wire rope terminations developed for mooring line applications (Figure No. 20) have performed very well in these tests.

An interesting test result was obtained in the testing of the 625 Inconel samples. Two ¼" 7x19 Aircraft construction wire ropes were retrieved after respectively 279 days and 294 days of immersion. Broken wires were found and a loss of strength of 29% was established. The cause of deterioration seems to be a combination of crevice corrosion and fatigue. Tow metallurgical laboratories (International Nickel and Massachusetts Institution of Technology) are further investigating the modes of failures of the broken wires.

Shackles. Round pin anchor shackles with galvanized steel cotter pins were used to connect the different components of the moorings as shown on Figure No. 31. When new, the pin of the shackle is held in place by its cotter pin. However, should the cotter pin deteriorate and break away the pin would then be free, and mooring motion would eventually force it out of the shackle jaws.

This clearly was the mechanism of failure of the ten parted moorings. Severely corroded and abraded cotter pins were found on all the retrieved moorings. Their distribution along the mooring line positively indicated that motion was accelerating the process. Cotter pins placed in shackles at the buoy, above and below the weight and in the chain chafing in the mud have failed, whereas cotter pins of shackles connecting the chain to the motionless anchor were found in excellent condition. Figure No. 35 shows an interesting progression converging towards the point of complete

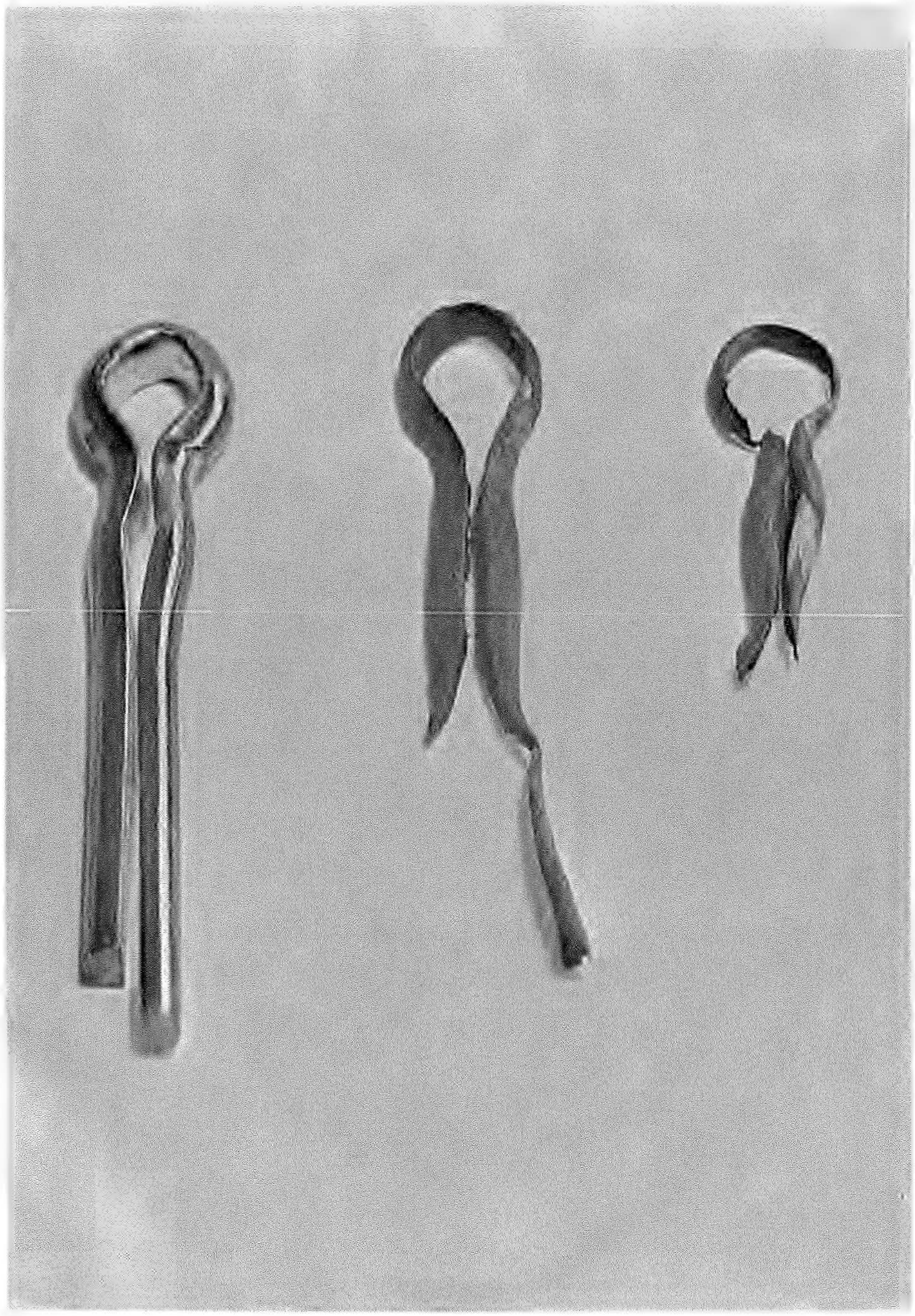


Figure 35. Deterioration of Cotter Pins

dissolution of cotter pins retrieved from these moorings.

As a consequence of this result, a different type of shackle is being evaluated for long term deep sea moorings. In this type the pin is a bolt held by a "stop nut" with a nylon insert backed up by a type 316 stainless steel cotter pin.

The pin and the body of the shackles submitted to motion and mechanical loading were found severely pitted and their original size was reduced as much as 30% after approximately 300 days of immersion. Figure No 36 shows a new shackle with the cotter pin of the type used in the "Buoy Farm", the same shackle as retrieved, and a new shackle with the bolt and lock nut of the type now in service.

The fact that no shackles were placed in the chain of the corner buoys explains why these moorings did not part. They would have failed however by chain abrasion and corrosion at the mud line if they had been kept on station another six months or less.

Chain. The shallow water tests indicate that under dynamic conditions severe pitting, stress corrosion, and abrasion on the bottom rapidly reduce the size and the strength of the chain (Figure No. 37). Laboratory tests show a 12% reduction of strength in chain sections immersed 225 days and exempt of abrasion and a 60% reduction in corroded and abraded sections of the same chain (near mud line).

Appendix No. 5.4 "Results of the Visual Inspection and Pull Testing of Wire Rope and Chain Samples Retrieved from the 1968 Shallow Water Test Array", is a detailed listing of the tests and test results performed at the Institution Laboratory on the samples retrieved from the "Buoy Farm"

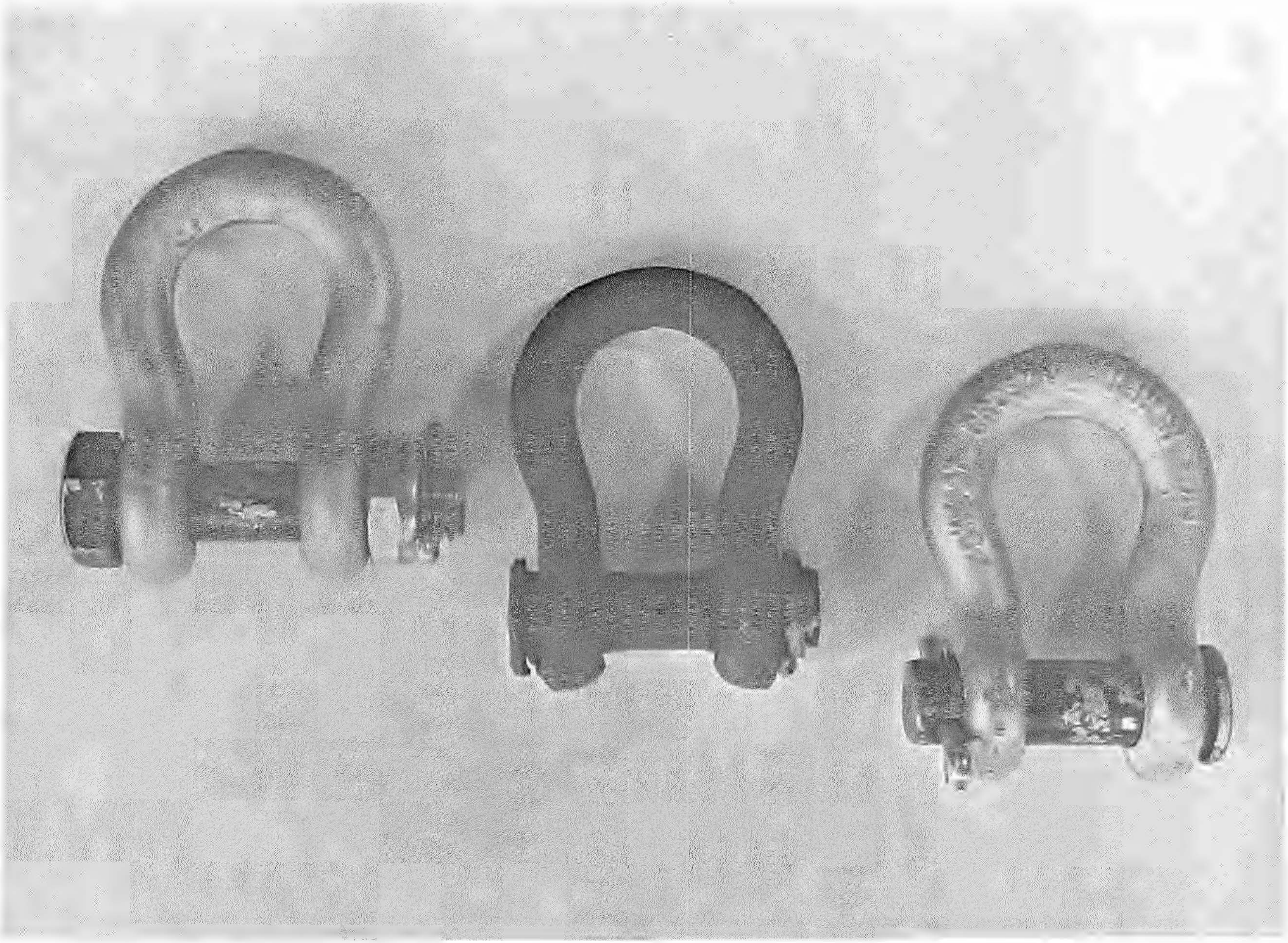


Figure 36. Deterioration of Shackles and New Type

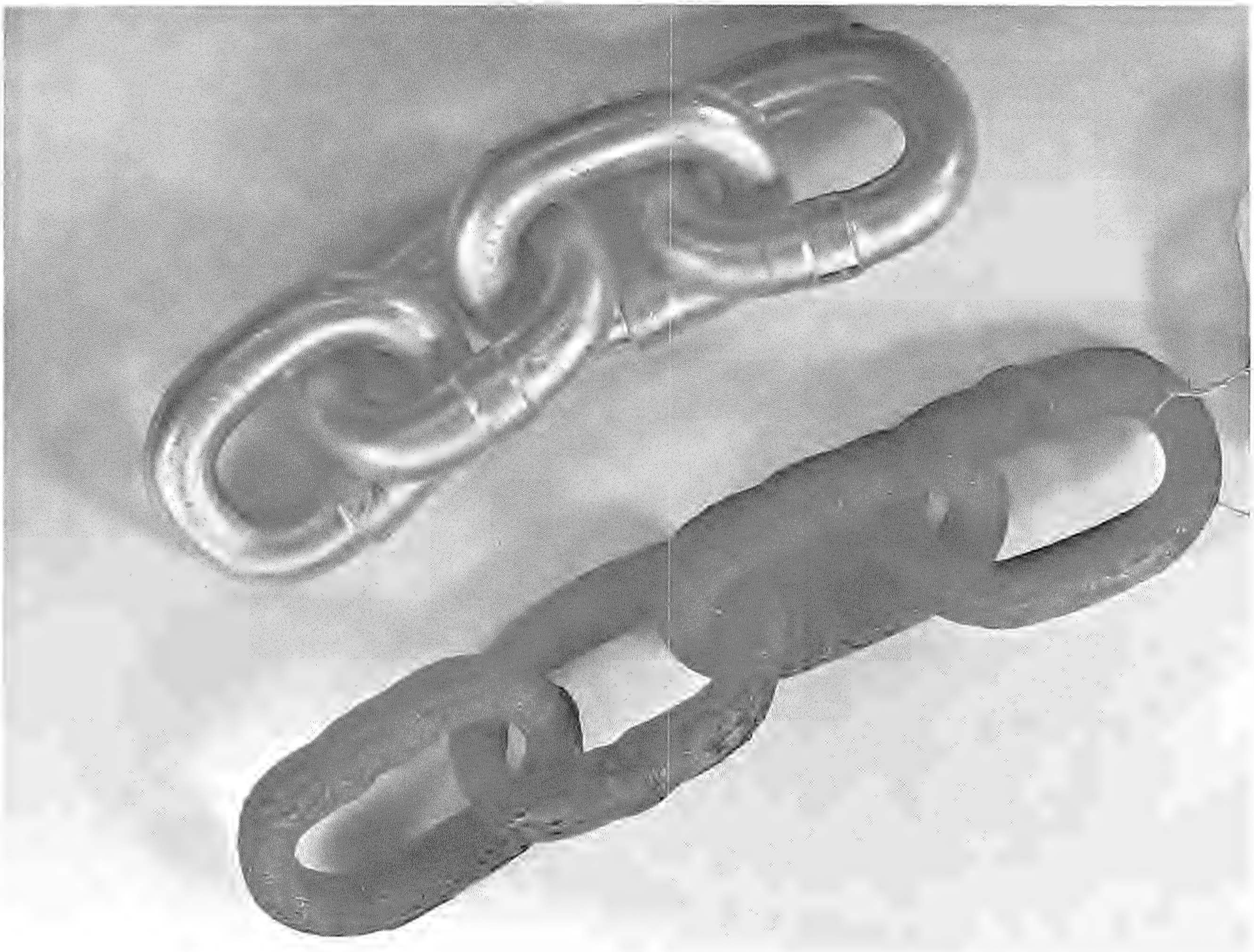


Figure 37. Deterioration of Chain

2.2 Experiments Conducted in Laboratories

In addition to the tests performed at sea a considerable number of land tests were performed on different mooring line components by, or for, the Woods Hole Oceanographic Institution, in 1968.

The purpose and the results of these complementary tests conducted in controlled laboratory conditions are hereafter reviewed.

2.2.1 Woods Hole Oceanographic Institution Test Program

The objectives of the Woods Hole Oceanographic Institution Test Program were to control the quality of the mooring line components acquired from industry, to observe the process of kink formation and determine the resulting damage on wire rope and strands for mooring line applications, and to establish certain elastic properties of nylon ropes of importance to compound buoy systems.

2.2.1.1 Quality Control. The performance history of components acquired from industry for mooring line applications is very limited. Furthermore in a single point moored system one defective component inserted in the line results in the failure of the whole system thus making systematic quality control of all components placed at sea a necessity. Tests for quality control purposes performed at the Institution were: pressure test of wire rope jacket and wire rope terminations, pull test to destruction of representative samples of chain and of wire and synthetic ropes and of their terminations, pull test to proof load of all components to be inserted in deep sea mooring lines.

<u>Pressure Tests</u>. Plastic jacketed wire ropes and their terminations when deployed deep must resist large hydrostatic pressures. The jacket is used for mechanical protection of the outer wires, for hydrodynamic drag reduction, for increase of the fatigue life of the rope, and as an additional protection against corrosion. The boot placed over the swaged fitting insures continuity of watertightness and provides mass transition for vibration damping. Should the pressure damage the jacket or force water in the boot then the integrity of the insulation is lost and the original purpose defeated.

Air occlusions and internal sharp edges of the fitting are usual causes of permanent damage to the boot under high pressure. Lack of material bonding between dissimilar plastics or plastic and metal is another frequent source of leaks at the boot.

The samples to be tested were terminated at both ends and pressurized for four hours at 3000 psi in the W.H.O.I. pressure tank. After removal, the samples were dried, and inspected. Boots were then opened up and a careful inspection made to find the presence of water in the boots or in the wires. Table No. VI "Summary of Pressure Test Results" presents the type of samples evaluated and the test results. Type 1 and Type 3 are essentially the same, yet their resistance to pressure is markedly different, which stresses the importance of quality control both at the factory and at the user's facility. Type 1 seems to perform best in these tests. Its main drawback is that it cannot be made in the field. Type 2, which can palliate this disadvantage will be further evaluated.

Pull tests to destruction. These tests were performed on samples of chain, wire ropes, and synthetic fiber ropes in the tensile test machine of the W.H.O.I.'s Laboratory (See Figure No. 38). These tests permitted the determination of the ultimate breaking strength of new samples and the holding power of their terminations. The actual breaking strength of wire ropes and strands was found to always exceed the manufacturers rated breaking strength. Table No. VII "Summary of Results - Pull to Destruction Tests" presents the average result of the numerous tests performed on these samples.

The actual breaking strength of nylon rope samples was found to be equal or slightly less than the manufacturers breaking strength. These samples were terminated at both ends with plices over a steel thimble, and pulled at a rate of one inch/minute.

Reduced holding power due to defective swaging was detected in two lots of samples and the corresponding mooring lines had to be reterminated by the suppliers in accordance with the W.H.O.I. specifications.

Pull tests to proof load. The safe working load of chain, shackles and sling links is usually defined as a load less than one half the load which would initiate yielding. A test load equal to 1.5 times the rated safe working load, should be able to detect faulty components which would yield prematurely. Such proof load tests were performed on hardware

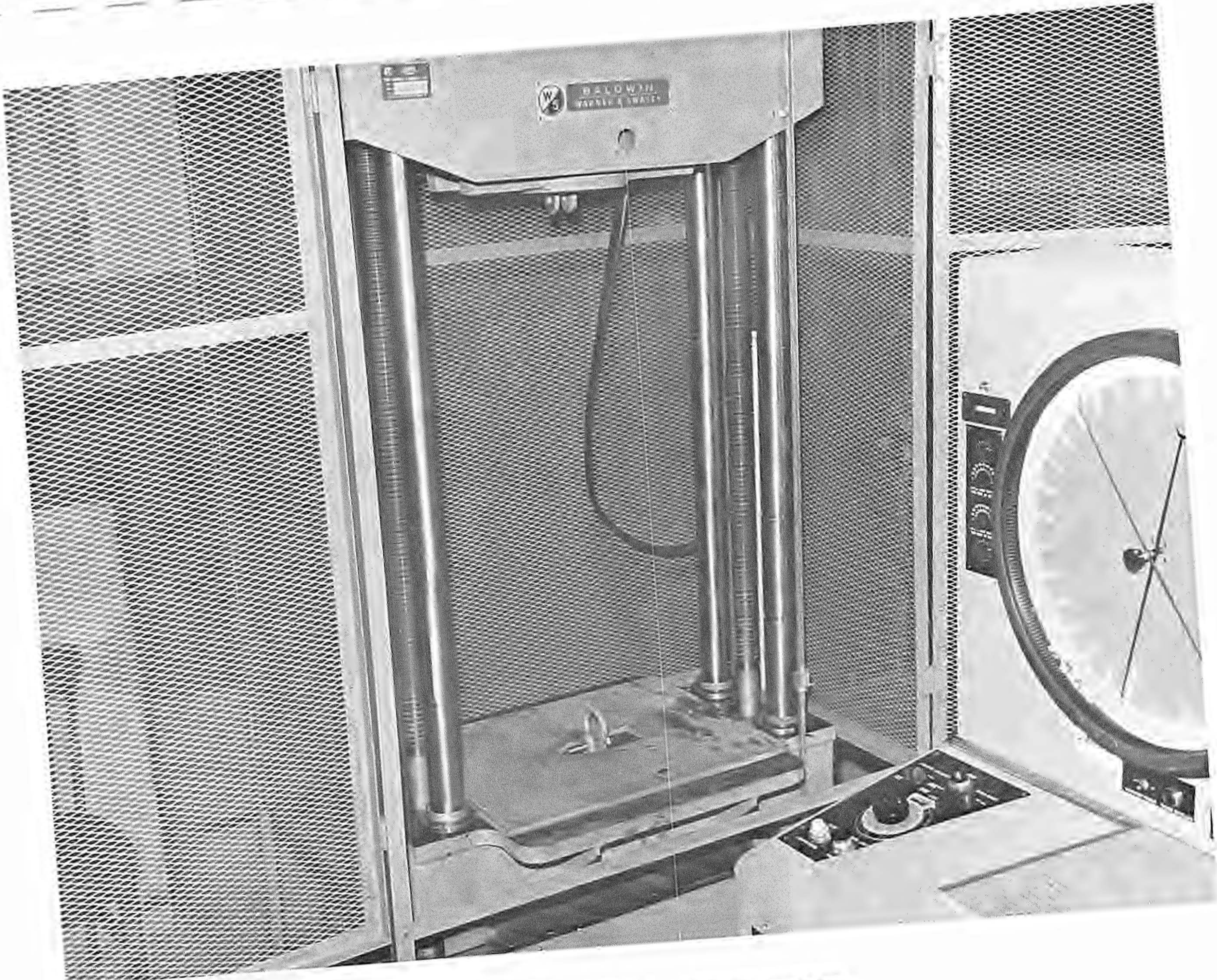


Figure 38. W.H.O.I. Testing Machine

TABLE NO. VI

Summary of Pressure Test Results

Type of Sample	Test Results	Remarks
Type 1 Torque balanced strand, ¼" 1x42 GAC, 9000 lbs. RBS, jacketed to .338 OD with Polyethylene. Termination made of central eye swaged fitting with molded boot of same material as jacket. Bonding agent on shank of fitting	Jacket in excellent condition. No water detected in the boot nor in the wires of the strand	Stiff boots- Good mold.
Type 2 Torque balanced strand, 9/32" 1x41 galvanized IPS, 9000 lbs. RBS, jacketed to 11/32" OD with polyethylene. Terminations made of central eye swaged fitting with a neoprene boot held in place by clamps. Leak tightness is insured by the internal molded rings of the boot.	No water detected after the first ring inside the boot. No water in the wires of the strand	Flexible boots - Good mold. Terminations can be made in the field. Clamps may corrode in long term applications. Rings may open up under dynamic loading.
Type 3 Torque blanaced strand, ¼" 1x50 galvanized IPS, 7690 lbs. RBS, jacketed to 5/16" OD with polyethylene. Termination made of central eye swaged fitting with small molded boot of same material as jacket.	Water detected in all boots. Jacket in poor condition near fitting, and water oozing out of the jacket.	Stiff and brittle boots. Poor quality of mold.
Type 4 Rope 9/32" 3x19 aluminized IPS, 9000 lbs. RBS, jacketed to 11/32" with polyvinyl molded boot over spring wrapping. Rubber cement and heat shrink tubing at the interface boot and jacket of rope further insure watertightness.	Water detected in a few boots under heat shrink tubing. Jacket in excellent condition.	Very flexible boot. Good mold. Heat shrink tubing poor water barrier.

TABLE NO. VII

Summary of Pull Test Results
(Full Break of Rope Samples)

Type of Sample	Average Ultimate Breaking Strength (lbs)	Metallic Area (sq. in.)	Average Ultimate Breaking Stress (psi)
Type 1-Torque Balanced Strand ¼" 1x42 Galvanized IPS	10,880	.038	286,000
Type 2-Torque Balanced Strand 9/32" 1x41 Galvanized IPS	9,940	.0408	239,000
Type 3-Torque Balanced Strand ¼" 1x50 Galvanized IPS	10,100	.0418	241,000
Type 4-Rope - 9/32" 3x19 Swaged Aluminized IPS	9,900	.0468	211,000
Type 5-Strand - ¼" 1x19 Galvanized Aircraft Cable	10,700	.0403	265,000
Type 6-Torque Balanced Rope 5/16" 3x19 Galvanized IPS	10,500	.04206	250,000
Type 7-Torque Balanced Strand ¼" 1x42 Galvanized Ultra High Strength	13,000	.038	332,000

to be used at sea, resulting in the rejection of approximately 1% of the tested components.

2.2.1.2 Process of kink formation. Mooring lines of single point moored buoys are essentially free end systems. During deployment the anchor end is free to turn, and after deployment, the buoy end is free to turn. Under tension strands and wire ropes with free ends have a tendency to unlay and open up, storing a certain amount of torsional energy in the line. If and when the tension is released the torsional energy may be sufficient to force the line to spring back and coil on itself. Such a condition results in loosening kinks and permanent damage to the rope, with subsequent failure of the mooring line (See Figure No. 39). This problem has been recognized (Ref. Nos. 1 and 6) and rotational data are available from most manufacturers.

The purpose of the tests performed at W.H.O.I. was to establish the rotation characteristics and the propensity to kink formation of wire ropes and strands of different configurations under test conditions which would approximate actual use. A 3800 lb. Stimson anchor of the type used in the Institution's deep sea moorings was attached to one end of the 100 foot long sample. The other end of the sample was secured to the boom of a crane, bypassing the crane swivel to prevent rotation of the sample at the upper end. The anchor was then lifted from the ground and allowed to spin - forcing the cable to unlay - revolutions were counted and when the anchor stopped turning, it was

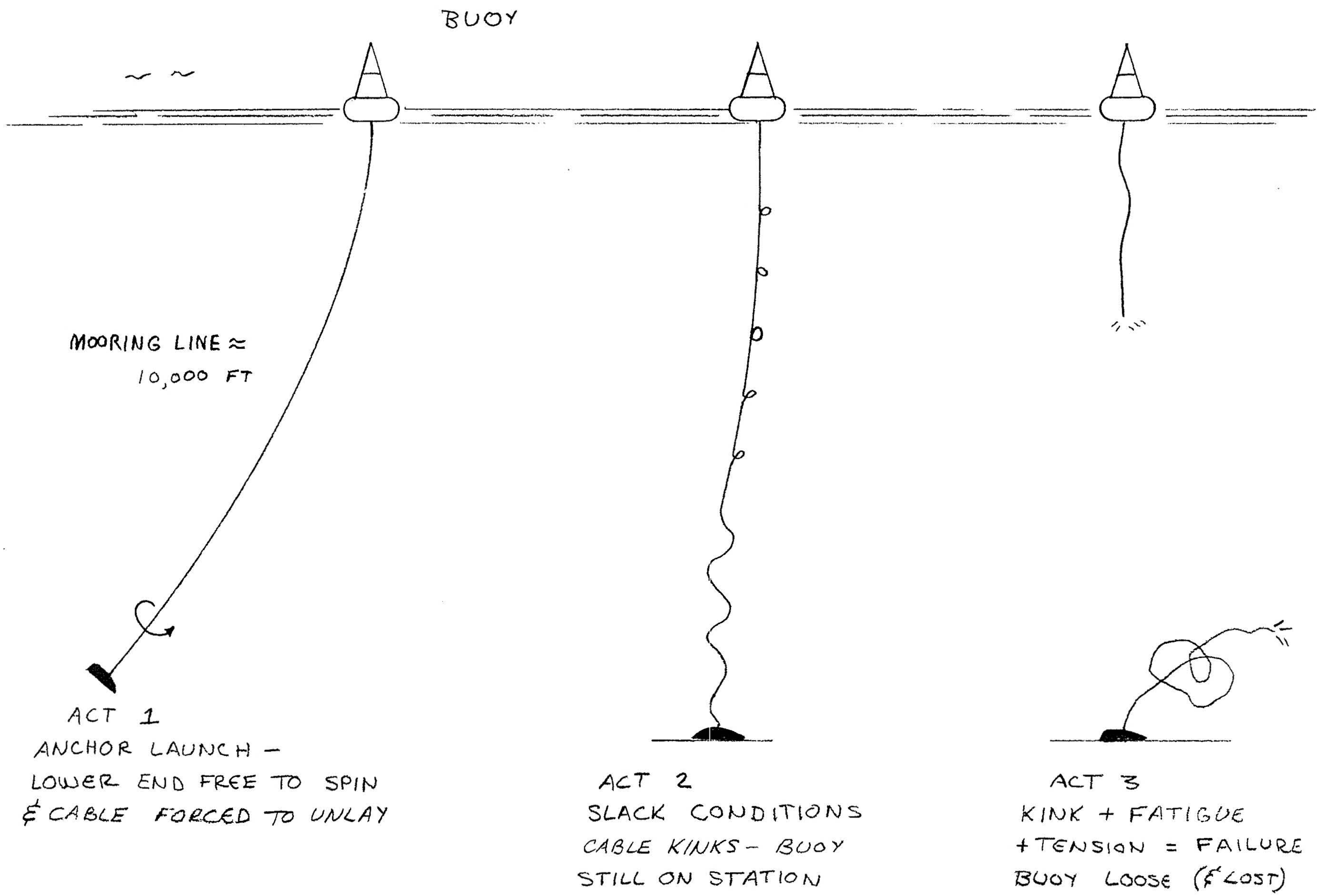


Figure 39. Process of Kink Formation During and After Free Fall of Anchor

lowered to the ground. The upper end of the sample was then lowered and the formation of loops and kinks was observed. (See Figures No. 40 and 41). Finally the sample was forced to lift the anchor once more and the subsequent damage to the jacket and the cable was noted. These tests were repeated with the anchor held to a complete stop at each revolution in order to determine the influence of the moment of inertia of the anchor on the total number of turns. These tests were also repeated with the anchor immersed in water in order to establish the incidence of the weight reduction and of the water drag.

The type of samples tested and the test results are shown in Table No. VIII "Summary of rotation test results".

The large number of kinks and the resulting damage obtained with non-torque balanced ropes seems to experimentally confirm a suspected cause of failure of deep sea mooring lines. On the other hand the excellent response of all the torque balanced ropes clearly indicate that spin free ropes should be recommended as mooring line components.

The difference in the number of turns under free spin and controlled spin conditions and under wet and dry conditions show the importance of the anchor moment of inertia and the damping effect of the water viscosity and mass.

TABLE VIII

SUMMARY OF ROTATION TEST RESULTS

Type of Samples	FREE SPIN IN AIR No. of Turns Per 100'	FREE SPIN IN AIR Comments	CONTROLLED SPIN IN AIR No. of Turns per 100'	CONTROLLED SPIN IN AIR Comments	FREE SPIN IN WATER No. of Turns per 100'	FREE SPIN IN WATER Comments
Type 1 ¼" 1x42 Gal. IPS Strand RBS - 9000 lbs	5½	1 slight kink. Jacket undamaged.	5½	No Loops No kinks Jacket undamaged	1	No loops No kinks Jacket undamaged
Type 2 9/32" 1x41 Gal. IPS, Torque Bal. Strand RBS - 9000 lbs	1½	No loops No kinks Jacket undamaged	½	No loops No kinks Jacket undamaged	1	No loops No kinks Jacket undamaged
Type 3 ¼" 1x50 Gal IPS Torque Bal. Strand RBS - 7690 lbs.	½	No loops No kinks Jacket undamaged			¼	No loops No kinks Jacket undamaged
Type 4 9/32" 3x19 Swaged Aluminized IPS Wire Rope RBS - 9000 lbs.	97	When tension in the line was relieved a large number of loops & kinks formed bu upon reapplication of the tension most of the kinks pulled out. Jacket split at kinks.	47	Large number of loops & kinks formed but pulled out when tension was reapplied. Jacket remained intact.	39	No severe kinks or damage to cable.
Type 5 ¼" 1x19 Gal. A/C Strand RBS - 8200 lbs.	41	3 loops & 5 kinks formed. Jacket was damaged at kinks. Strand parted at worst kink when anchor was lifted. Kinks form easily and do not pull out.	20	Few loops, 3 kinks formed, the jacket was damaged at the kinks. Strand parted at worst kink when the anchor was lifted.	16¼	Several loops & 2 kinks formed. Jacket damaged at kinks. Strand remained intact.

Types of Samples	FREE SPIN IN AIR No. of Turns per 100'	FREE SPIN IN AIR Comments	CONTROLLED SPIN IN AIR No. of Turns per 100'	CONTROLLED SPIN IN AIR Comments	FREE SPIN IN WATER No. of Turns per 100'	FREE SPIN IN WATER Comments
Type 6 5/16" 3x19 Gal. IPS, Torque Bal. Wire Rope RBS - 10,300 lbs	0	No loops No kinks				
Type 7 ¼" 7x19 Gal. A/C Wire rope RBS - 7000 lbs	464	Very large number of kinks formed, wires broken at lower termination. Jacket split in many places. Anchor revolved very fast.			240	Many kinks. formed. Jacket undamaged. 1 whole strand broken.

Figure 40. Loops Formed in Wire Rope Samples

Figure 41. Damaged Rope at End of Test

2.2.1.3 Elastic properties of nylon ropes

In order to limit the excursion and to prevent the formation of kinks in compound moorings, a minimum level of tension and stretch must be maintianed at all times in the line. This can be achieved only if the depth of the water, the unstretched length of the line, and the elastic response of the line to the loads encountered at sea during and after launch are precisely determined. The tests performed to investigate this response and their instructive results are hereafter briefly reviewed.

First cycle of loading - The question that the designer of taut moorings has to answer is: What is the length of unstretched rope which will permit a preset tension to be obtained when stretched to a known and fixed length?

To answer this question the elastic response resulting from the load history must be known. This information cannot be derived from the standard curves of % elongation versus % of breaking strength provided by the manufacturers. These curves are based on averaged values obtained after one or several load cycles and are of little help if the rope is to be used for the first time.

A typical response to a first loading cycle is shown in Figure No. 42. It can be seen from this curve that the value of elongation corresponding to a given load is not uniquely determined, but is related to the loading

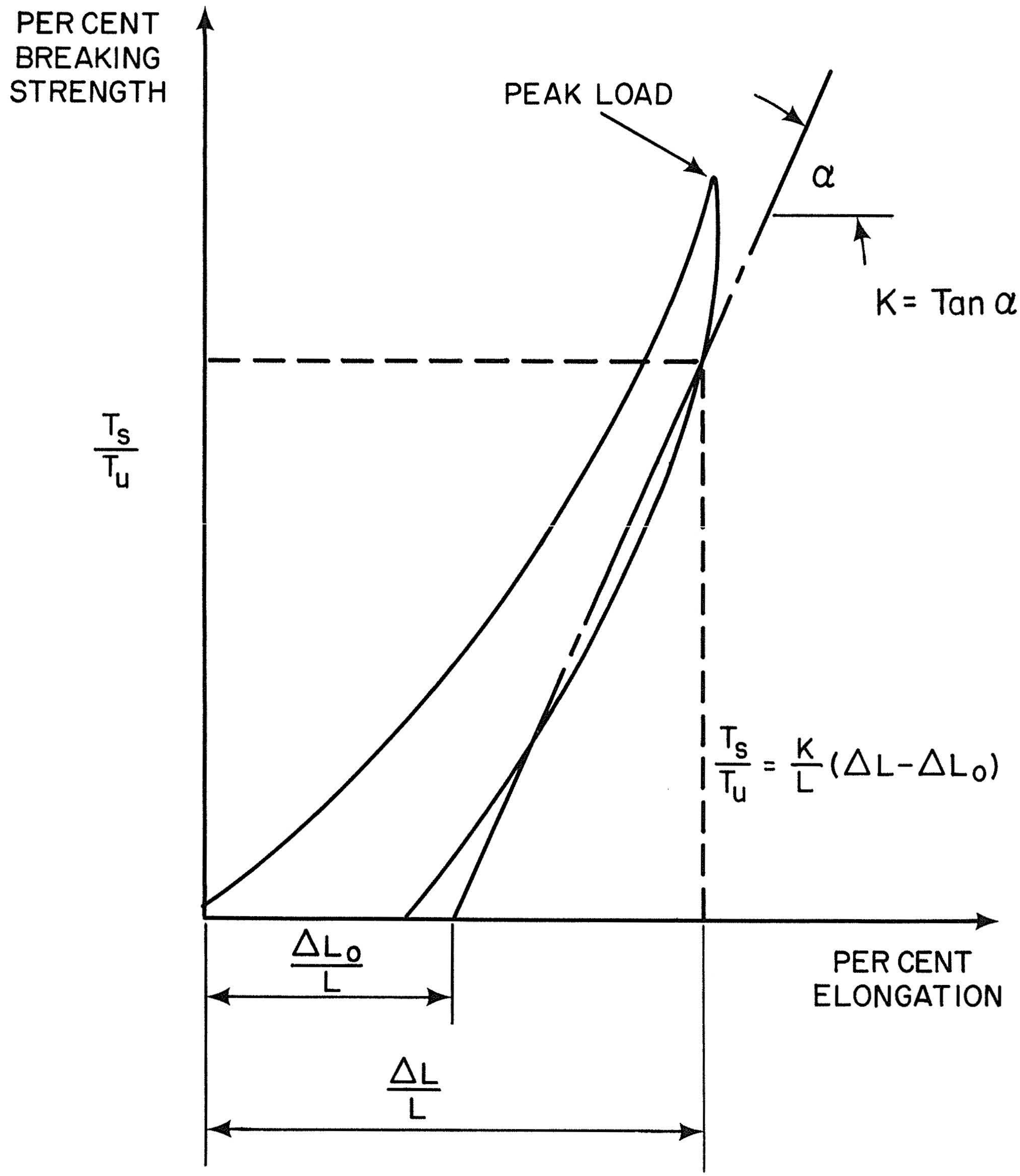


Figure 42. Nylon First Loading Cycle

sequence. If the line is first stressed to the maximum load and then slowly relaxed the percent elongation for a given load is given by the second branch of the hysteresis loop. Furthermore, elongation percentage smaller than the percentage at return will result in zero tension.

Mooring lines undergo such a loading sequence during deployment. A high tensile force is applied during the launching when the anchor is pulling and stretching the line until it reaches the sea floor. After the anchor has bottomed the tension decreases to a lower value determined by winds, currents, and percent elongation of the mooring line original length. First loading curves for 9/16" and 5/8" nylon plaited ropes were established in the Institution Test Laboratory using values of peak loads obtained from measurements made at sea during deployment. (See Figure No. 43). The % elongation necessary for a minimum tension could then be predicted. For example, to 16% elongation would correspond 500 lbs. of minimum tension in a new 5/8" nylon rope first loaded to 2000 lbs. Measurements made at sea approximately confirmed the validity of such predictions. In particular it was noted that low percentage of elongation (7%or less) resulted in zero tension in the mooring line.

When used for the second time, the elastic response to the expected load cycle should be re-investigated and the percentage of elongation determined by the new experimental results.

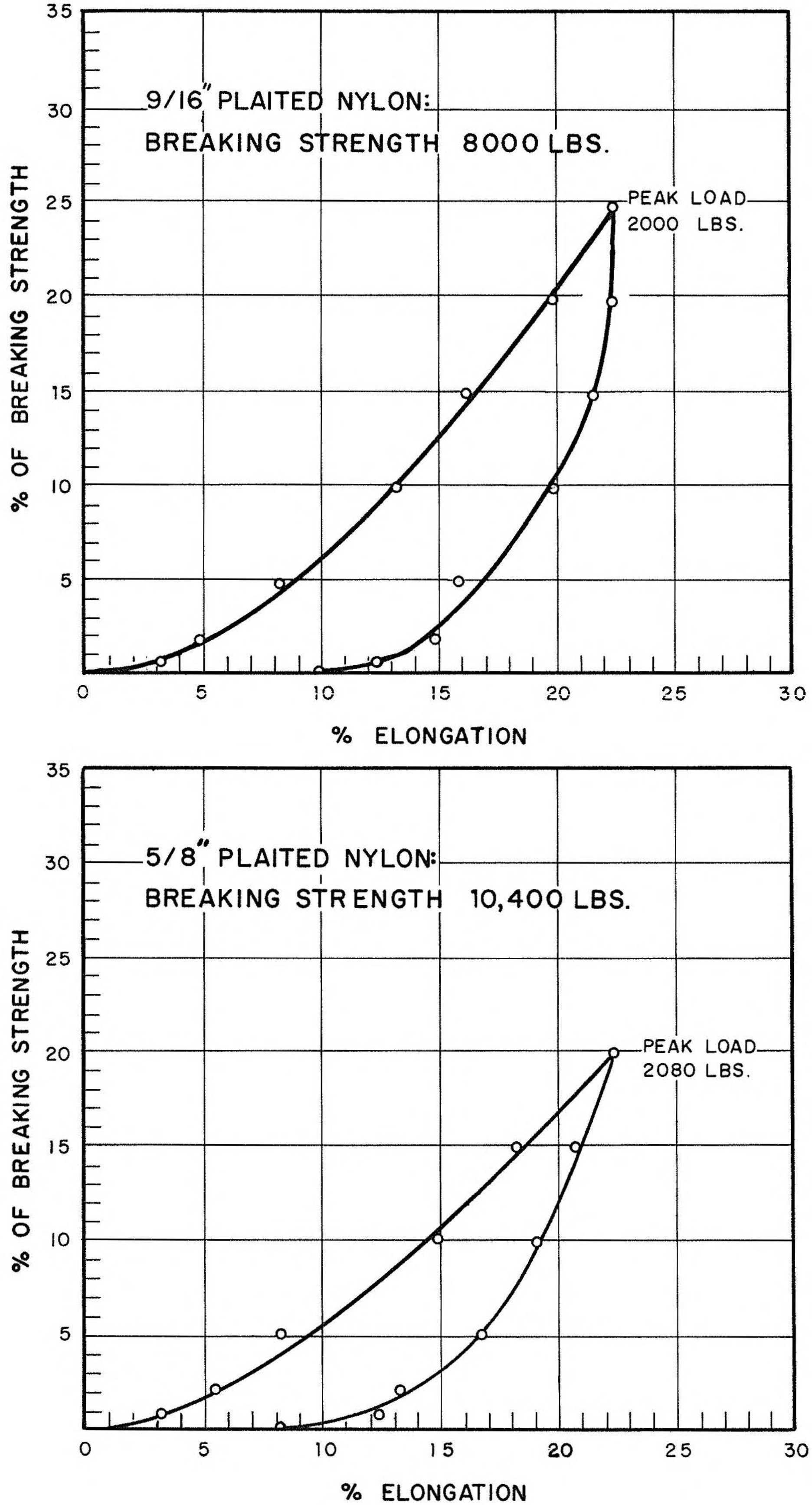


Figure 43. First Loading Curve for 9/16" and 5/8" Plaited Nylon

Creep - Loads greater than 30% of breaking strength are rarely applied to nylon ropes for periods of months. In taut mooring lines however, loads of 15% to 30% of the breaking strength are sustained for long periods of time. In order to investigate the effects of the constant application of tension a simple experiment was conducted on a 12 foot sample of new 5/8" plaited nylon rope.

The sample was spliced at both ends and a "free" length excluding the splices measured at 200 d^2.* It was ten secured to a tripod and a 3450 lb. anchor representing 33% of breaking strength) was suspended at the lower end. Measurements were made at regular intervals over a period of three months. The results are depicted in Figure No. 44. The instantaneous initial elongation was 33%. The elongation due to creep took place mostly in the first few days of the test. At the completion of the test the elongation was 40% under full load. When measured at 200 d^2 the elongation was 15% at the same time, but was found reduced to 11.5% ten days later.

2.2.2 Tests Performed with Consulting Laboratories

A Study of wire rope response to cyclic and torsion loads, and the metallurgical analysis of samples of interest were conducted for the Institution by consulting laboratories.

*It is standard industrial practice to measure fiber ropes at a tension equal in pounds to 200 times the diameter squared in inches.

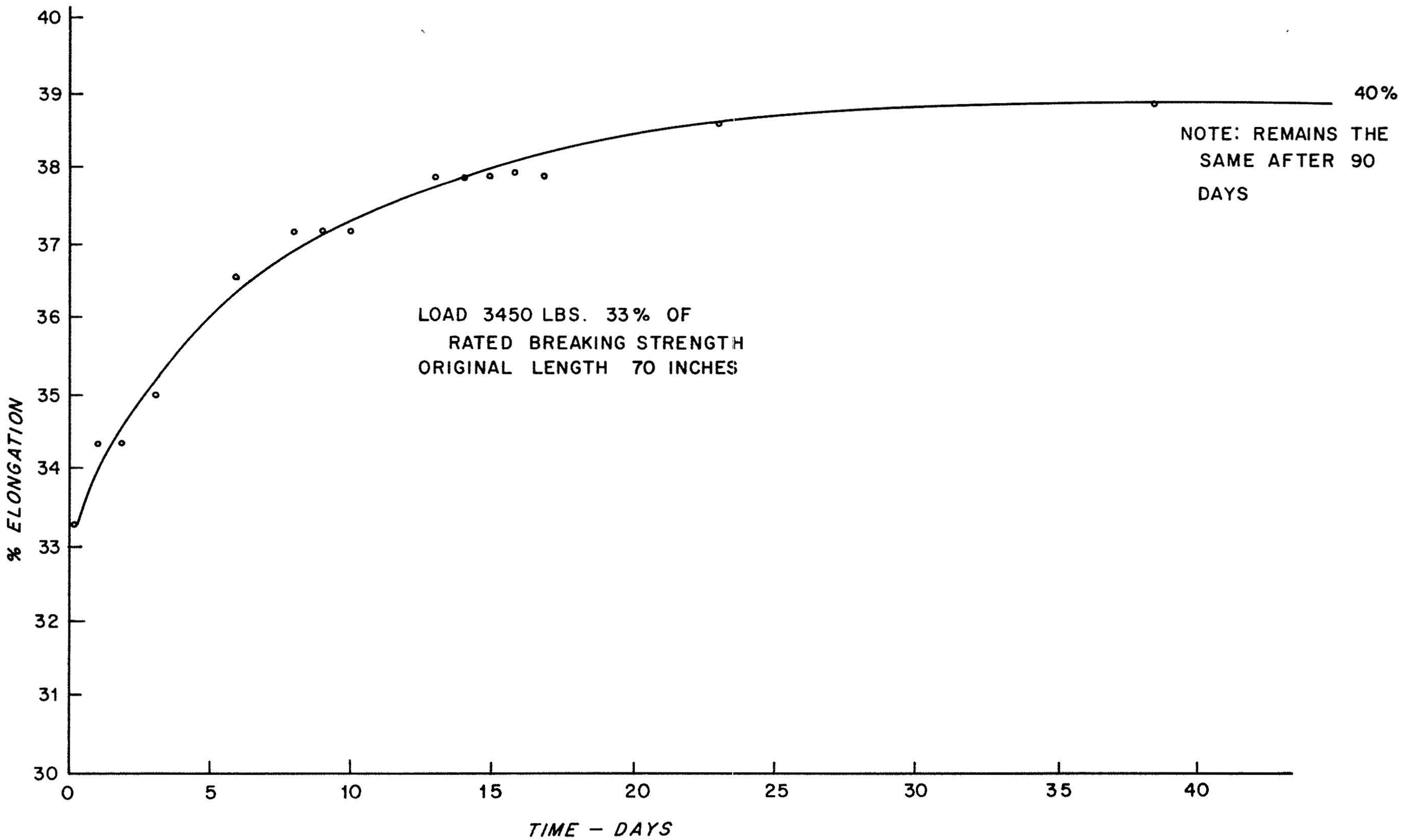


Figure 44. Elongation Versus Constant Load on 5/8" Plaited Nylon

2.2.2.1 <u>Cyclic Load Tests</u>

The purpose of these tests was to evaluate under controlled laboratory conditions the performance and the endurance limit of samples of wire ropes submitted to cyclic loadings. Measurements made at sea together with engineering judgment determined the types and the magnitude of the test loads which would result in a reasonable approximation of the field conditions. Three types of tests were conducted: cyclic tension, cyclic impact, and vibration. The cyclic tension tests simulated the periodic variations, around a mean, of the longitudinal stresses due to wave action. The cyclic impact tests simulated the high energy impact loading possibly imposed on the mooring cable by rapid motion of the surface buoy during bad weather . The vibration tests simulated the strumming conditions induced by vortex shedding of taut mooring lines set in strong currents.

These tests were all performed on the same type of wire rope: ¼" 1x19 galvanized Aircraft strand. The vibration tests have shown that strumming (small amplitude high frequency vibrations) was not a problem for the particular configuration under study. (Polyethylene jacketed strand with boots of same material molded over swaged fittings).

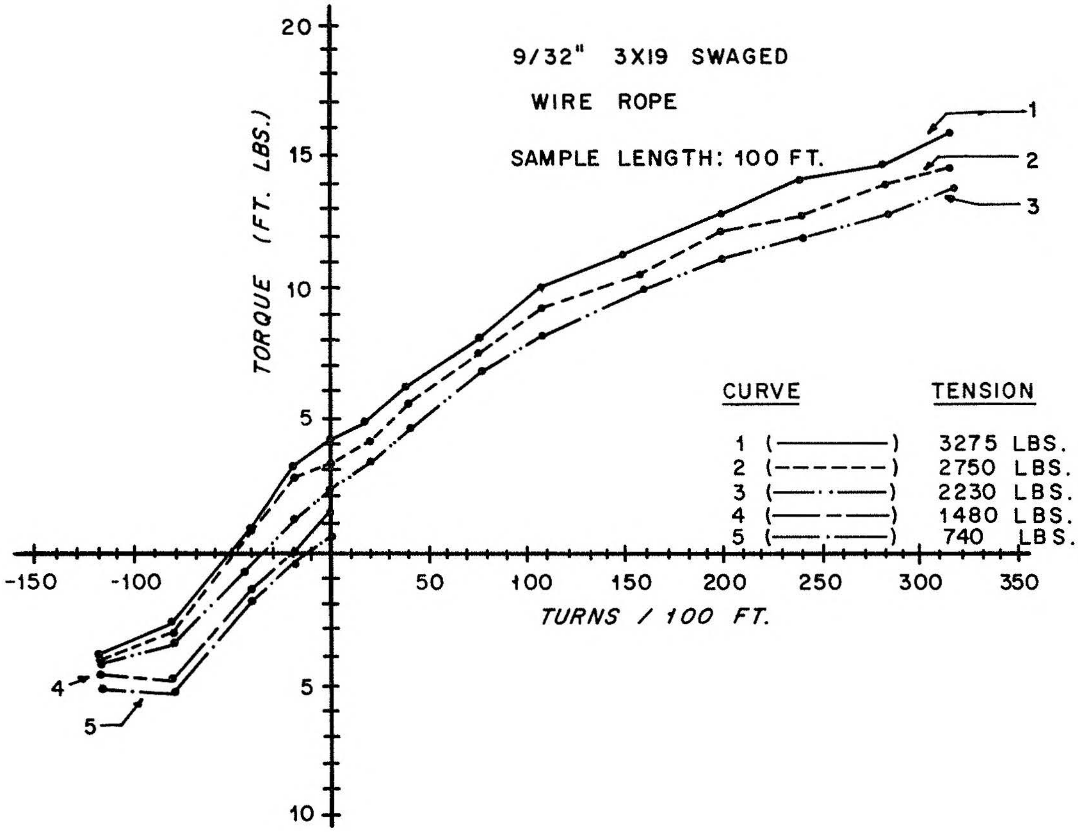
On the other hand the impact tests and the longitudinal cyclic tension tests have stressed the importance of reducing the levels of both the average and the fluctuating loads. This immediately suggests large safety factors and means of either damping or isolating the surface effects (shock absorbers, or surface buoys decoupled from wave action). In addition to this intrinsic information this series of tests has established a tentative base for the evaluation of the relative merits of ropes of different constructions and materials.

These tests were performed at the mechanical laboratories of the Preformed Line Products Company, Cleveland, Ohio. Values of test loads, experimental set up, and detailed results are presented in Appendix 5.6.

2.2.2.2 Torsion Load Tests

The purpose of these tests was to quantitatively determine the torsional and spring characteristics of different wire rope configurations and to study the relation between these parameters and the propensity to kink formation. To this end two series of tests are being conducted by the Instrumentation Laboratories of the Massachusetts Institute of Technology (Mr.W. Vachon).

In one series of tests a number of turns are forced into 100 foot long samples at various tension levels and the corresponding induced torque and elongation are measured and recorded. Turns are forced against the lay and also with the lay. Figures No. 45 and 46 show two (2) typical sets of curves of torque versus number



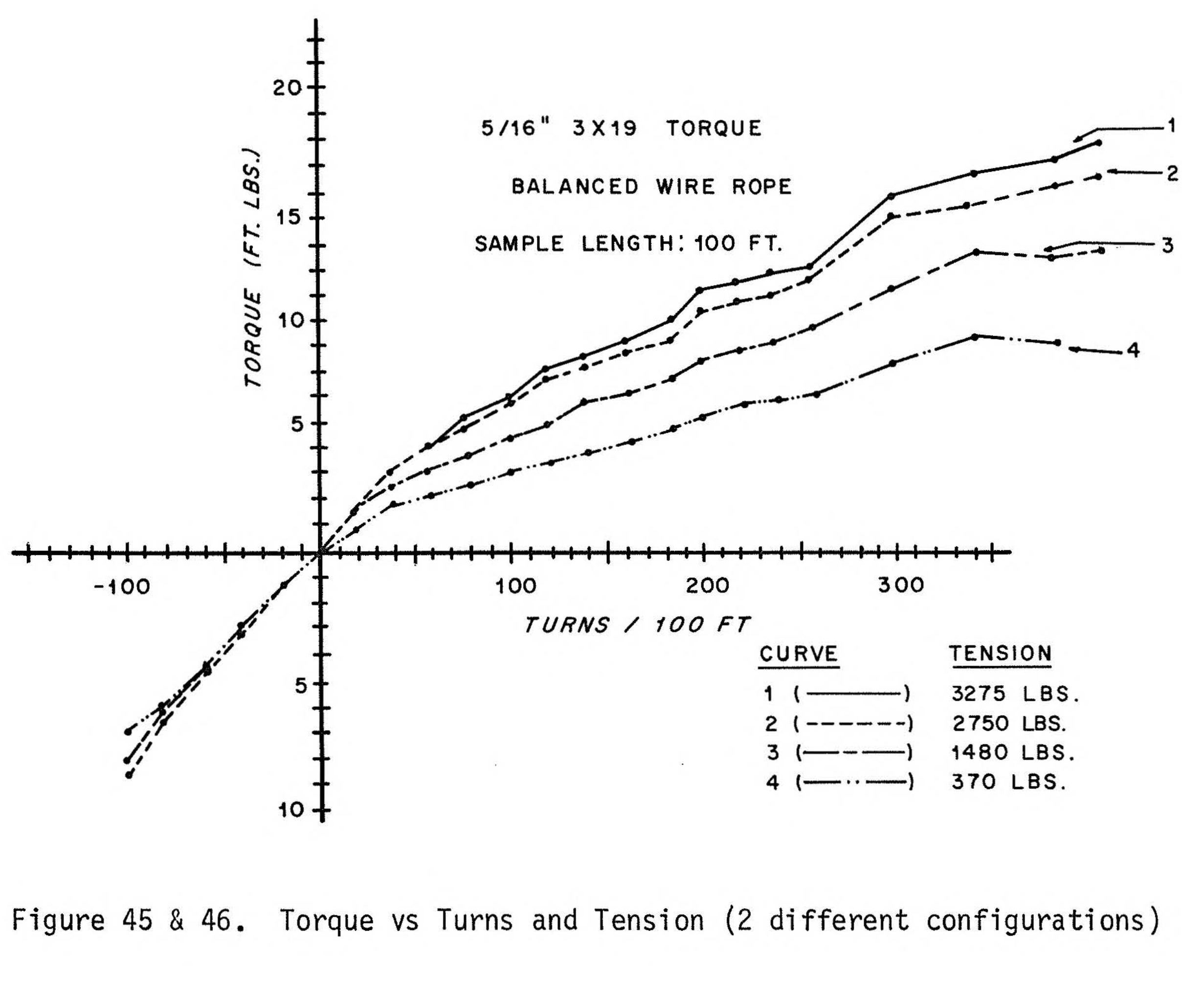
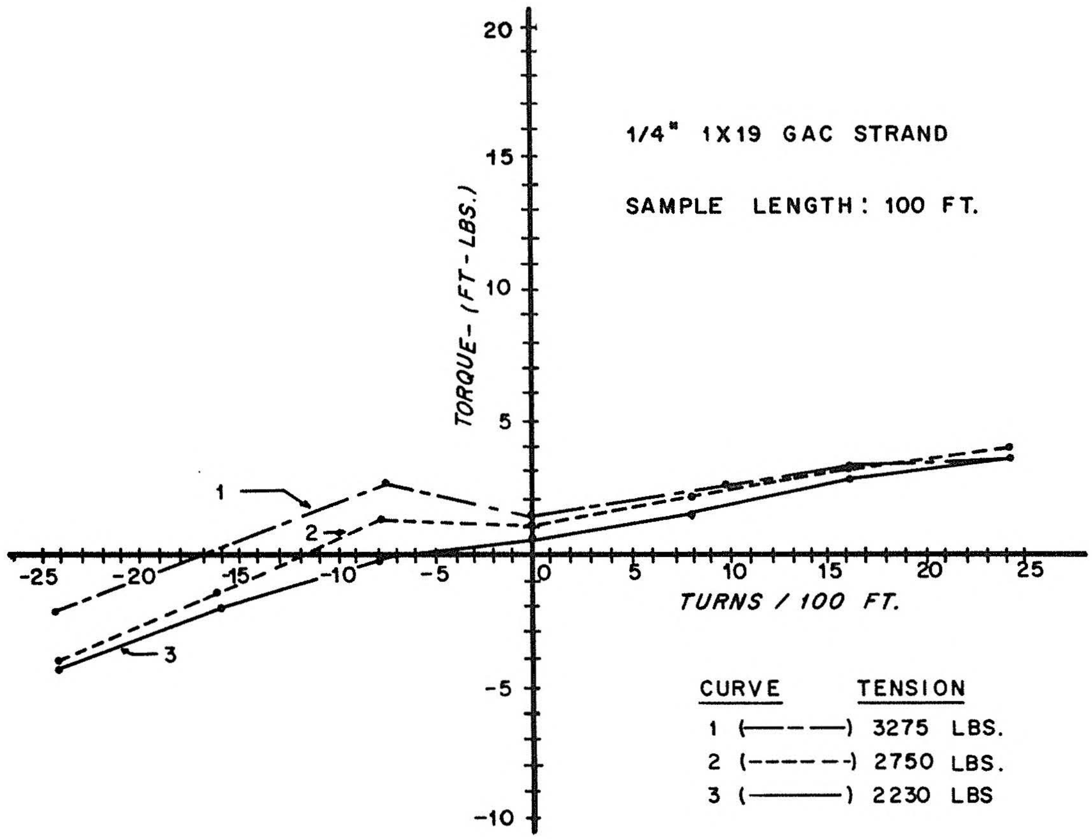
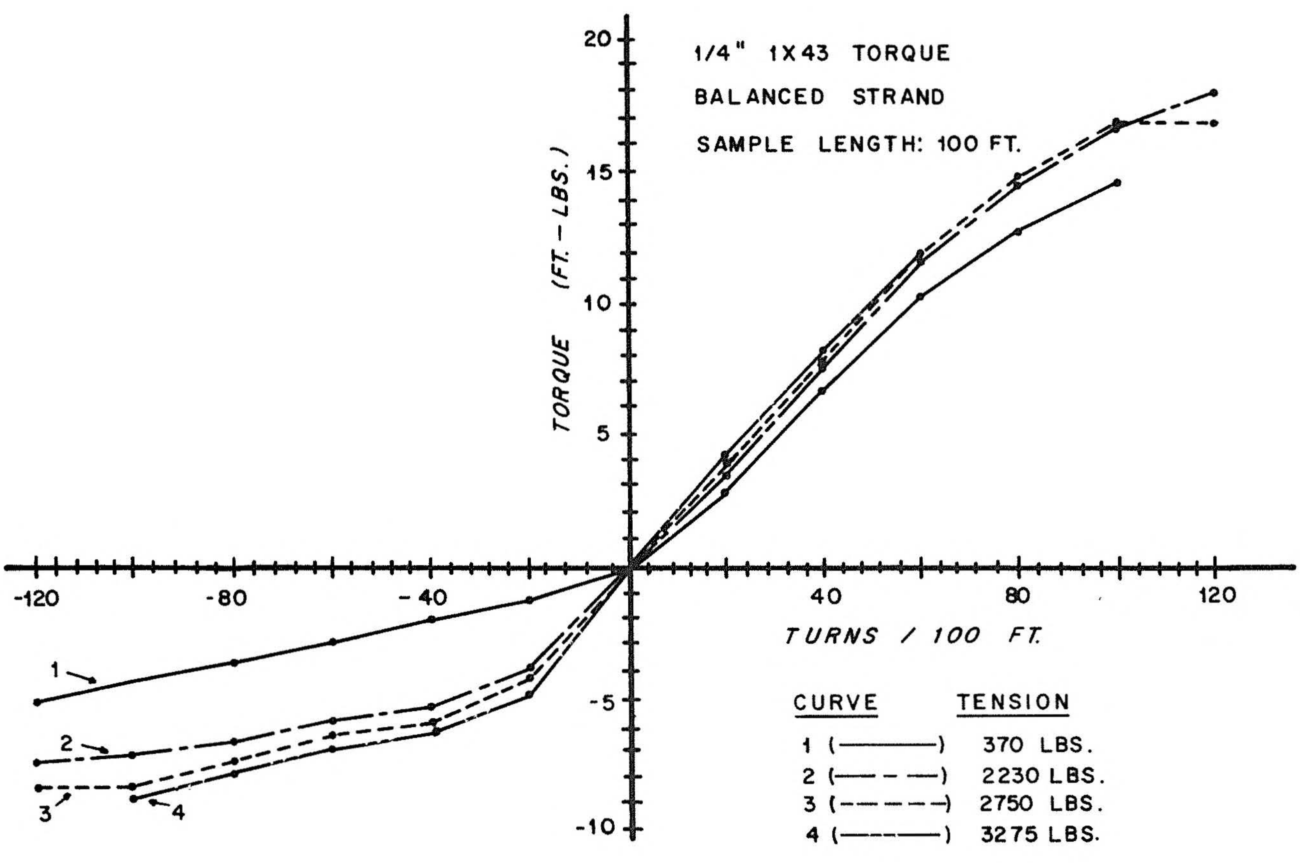


Figure 45 & 46. Torque vs Turns and Tension (2 different configurations)



1/4" 1X19 GAC STRAND
SAMPLE LENGTH: 100 FT.
TORQUE- (FT-LBS.)
TURNS / 100 FT.
CURVE TENSION
1 (— — —) 3275 LBS.
2 (- - - - -) 2750 LBS.
3 (———) 2230 LBS



1/4" 1X43 TORQUE
BALANCED STRAND
SAMPLE LENGTH: 100 FT.
TORQUE (FT.-LBS.)
TURNS / 100 FT.
CURVE TENSION
1 (———) 370 LBS.
2 (— — —) 2230 LBS.
3 (- - - - -) 2750 LBS.
4 (—·—·—) 3275 LBS.

Figure 46.

of turns obtained at different tension levels for wire ropes and strands. The number of turns under free end conditions and for a given tension is found at the zero torque ordinate.

The torsional spring constant at a given tension value is defined as

$$\mathcal{T} = \frac{\partial M}{\partial n}\Big|_{n=0}$$

where $\mathcal{T}$ = torsional spring constant (ft-lb/turn)

M = f(n,T) torque, function of n and T, (ft-lb)

n = number of turns

T = Tension (lb)

Its magnitude is a measure of the resistance to rotation of a given wire rope at a given tensile load. The higher the torsional spring constant the higher the torque needed to induce turns in the rope.

In a second series of tests, the kink formation threshold is determined by measuring the critical tension needed to prevent loop throwing in different samples under given conditions of torque.

The experimental data obtained from these two series of tests should further help the designer of mooring systems in the selection of the configuration of rope to use and of the minimum tension levels to keep in the line.

A detailed report, outlining the test procedures and significant results will be presented by M.I.T. at the completion of the present experimental study (summer 1969).

2.2.2.3 Metallurgical Analysis

The metallurgical analysis of the samples showing deterioration and damage from either sea or laboratory experiments is being conducted at the Instrumentation Laboratory of M.I.T. (Mr. R. Morey). Modes of failure (fatigue, tensile, shear, corrosion or combination) are determined by the examination of the fracture faces. Metallurgically polished and etched samples are investigated to further observe the process of deterioration (fatigue cracks, abnormalities, path and extent of corrosion penetration, etc.).

The results of this continuous effort will be an important factor in the selection of materials and in the improvement of the design of mooring line components.

3. Radio Telemetry

A radio telemetry system was developed to measure certain surface parameters and transmit them to the laboratory at Woods Hole. Real time monitoring of events including the passage of high currents through the area, periods of high winds and surface temperature changes can thus be related to mooring losses or damage in addition to scientific benefits.

The present system transmits a digital message once every four hours consisting of wind speed and direction, current speed and direction, and water temperature. The transmission is initiated by an internal clock, however, a command receiver will be added in the near future. A channel in the 4MHz Ocean Data Service band is employed using frequency shift keying. A return-to-zero (RTZ) code is used with a frequency shift of ± 85Hz. Digital data from the current meter in W.H.O.I. standard format followed by similar data from the wind recorder permits standard processing of received data ashore with little program modification. Temperature at the current meter and at the surface buoy is digitized and inserted in the last rotor word of the current meter message and again in the last anemometer word. Between telmetry transmissions the transmitter is modulated at a lower duty cycle by a tensiometer below the buoy. The tensiometer produces a series of pulses whose number and position in time, identify the unit and indicate the tension value.

A test of the system was made from station D in December. Thirty-one consecutive hourly transmissions were received at Woods Hole and recorded. Seven samples of each compass and vane were sampled consecutively and transmitted to permit averaging using their orthogonal components. Signal levels as received at Woods Hole averaged 8 microvolts/meter, generally higher than the noise background.

A ten watt frequency shift transmitter and control unit was mounted, together with batteries in the instrument well of the telemetry buoy (see appendix 5.5 Telemetry Buoy Data Sheet) for these tests. A center-loaded whip antenna is mounted at the apex of the tower above the wind sensor.

Tension Telemetry - The majority of buoys deployed in the past year have been equipped with tensiometers placed immediately below the surface buoy. These units produce a series of pulses which key the radio beacon transmitter. These pulses identify the buoy and by pulse position modulation indicate the tension value. Monitoring from shore will thus indicate a parted mooring (reduction in average tension), the state of the sea (bandwidth of the scatter) or the presence of high winds or currents (increased tension). A more reliable solid-state tension encoder has been developed eliminating a motor used in previous units. All buoys deployed in the future will incorporate tension telemetry in the beacon signal.

Conclusion.

The study of the line response has established the necessity of controlling the length measurements and the load history of the synthetic fiber ropes in order to achieve a given level of pretension in taut moorings. The analysis of the tension data has indicated a wide range of static and dynamic tension values, strongly related to surface and near surface environmental conditions. It seems that corrosion is not a factor of deterioration and failure for the type of deep sea moorings described. Fatigue failures are possible, the detection of deterioration due to fatigue prior to failure of one or more wires remains extremely difficult.

Comprehensive measurements of the line response could reveal the possibility of single event failures due to extreme ranges of loadings (relaxation, impact, torsion). Such a study requires sophisticated instrumentation which can be programmed to sample and record thse events over a large range of environmental conditions.

Rotation tests have indicated a much better performance of torque balanced wire ropes and strands for free end application. Cyclic tests indicated that longitudinal low frequency cyclic loads are much more detrimental than lateral high frequency vibration. Torsion tests have proved that twisting of the rope may result in a drastic reduction of strength.

Further testing in shallow water and in laboratories will be continued in 1969 to further delineate the suitability of a number of wire rope configurations. Engineering measurements made at sea should further and better establish the response of deep sea mooring lines.

Setting and maintaining single moored surface buoy systems in large depths is still a difficult problem. More fundamental and applied research is required to bring the reliability of the structural components up to the performance level of the sophisticated instrumentation that they are required to support in the sea environment.

An attempt to provide a measure of statistical significance to the shallow water mooring tests has been made by exposing pairs of samples. The same reasoning should be extended to deep sea mooring tests.

LIST OF REFERENCES

Ref. Numbers	Description
1	Berteaux, H. O., "Surface Moorings, Review of Performance", Woods Hole Oceanographic Institution Report, Ref. No. 68-20, March 1968.
2	Berteaux, H. O. & Walden, R. G., "The Mooring Wire Testing and Evaluation Programs for 1968", Woods Hole Oceanographic Institution Technical Memorandum No. 7-68, March 1968.
3	Berteaux, H. O, "Introduction to the Statics of Single Point Moored Buoy Systems", Woods Hole Oceanographic Institution Technical Memorandum No. 11-68, May 1968. (Lecture Notes to M.I.T. Course)
4	Berteaux, H. O. & Heinmiller, R. H., "Back Up Recovery Systems of Deep Sea Moorings", Woods Hole Oceanographic Institution Report, Ref. No. 69-7, February 1969.
5	Heinmiller, R. H., "A Test of A Swivel on A Deep Sea Mooring", Woods Hole Oceanographic Institution Technical Memorandum No. 13-68, May 1968.
6	McLoad, K. W., "Torque Balanced Wire Rope and Armored Cables", Transactions of the 1964 Buoy Technology Symposium, Marine Technology Society, Washington, D. C., March 1964.
7	Martin, W. D., "Tension and Geometry of Single Point Moored Surface Buoy System - A Computer Program Study", Woods Hole Oceanographic Institution Report, Ref. No. 68-79, December 1968.
8	Millard, R. C. "Observations of static and dynamic tension variations from Surface Moorings", Woods Hole Oceanographic Institution Report, Ref. No. 69-29, May 1969.

DERIVATION OF ANCHOR FREE FALL ULTIMATE SPEED
APPENDIX 5.1

1. Average speed

The average speed $\bar{v}$ is defined as

$$\bar{v} = \frac{D}{t}$$

where D is the depth of the water and

t is the time elapsed between "anchor overboard" and "anchor bottoming"

Example. Station No. 278 - D = 2680 meters

t = 29.5 minutes

$\bar{v}$ = 1.52 m/sec = 4.97 ft/sec

2. Speed of free fall

The ultimate speed of free fall is defined as

$$S = \frac{D_1}{t_1}$$

where D is the depth reached when the anchor starts pulling on the mooring line (end of phase 1 of launching transient)

and t is the time of free fall (length of phase 1)

It can be seen from Figure No. 47 that D_1 is given by

$$D = \ell \cos \alpha = \ell \frac{W_s}{T_s}$$

where 1 is the unstretched length of the mooring line

W_s is the weight of the mooring line at the surface

T_s is the Tension at the surface at the end of phase 1

Example. Station No. 278 h = 2500 m.

W_s = 670 lbs.

T_s = 880 lbs.

t = 1000 sec.

then S = 1.9 m/sec = 6.3 ft/sec

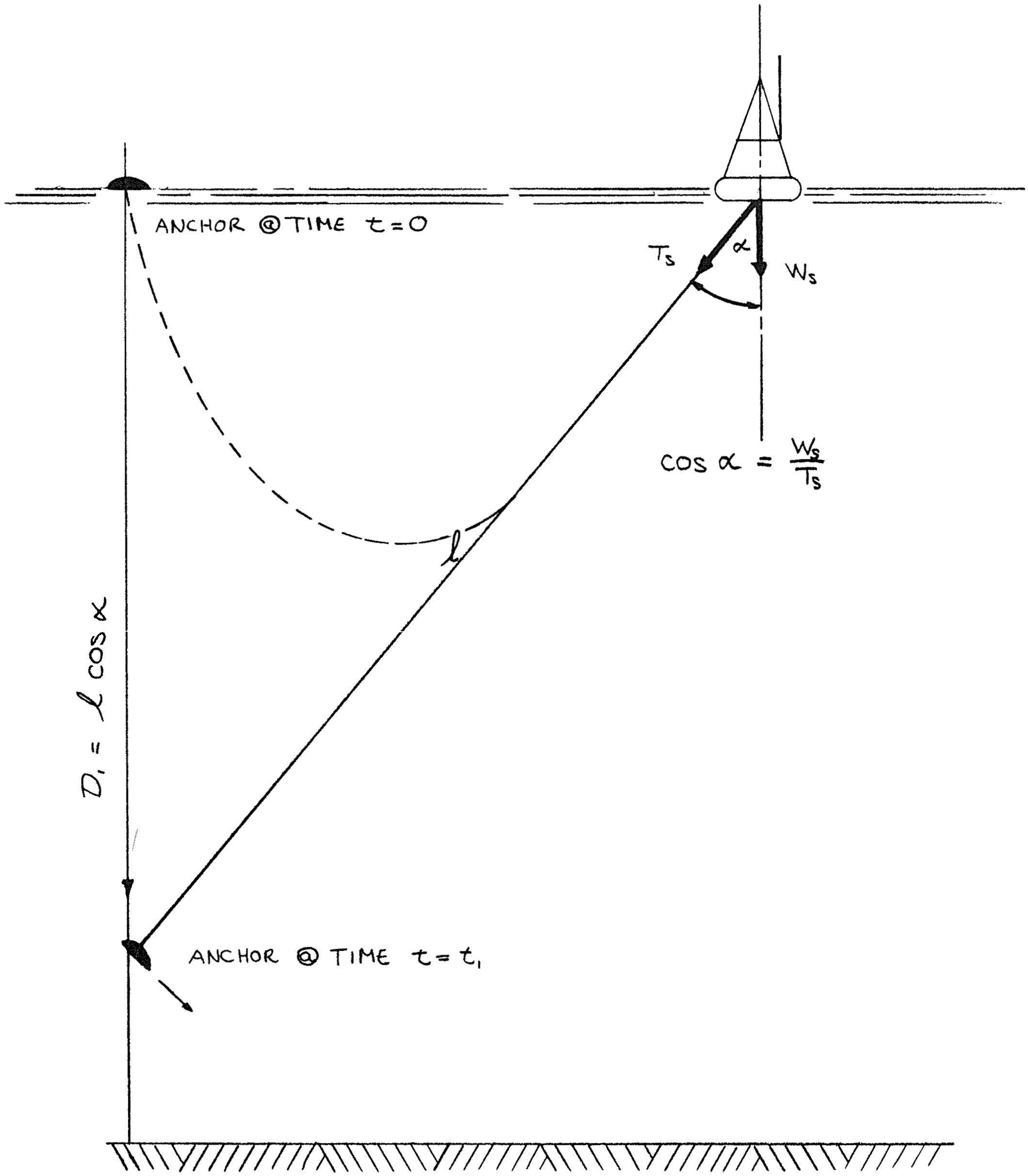


Figure 47. Anchor Free Fall (A - I)

APPENDIX 5.2

Formula for computing the length of synthetic fiber components in a taut mooring line.

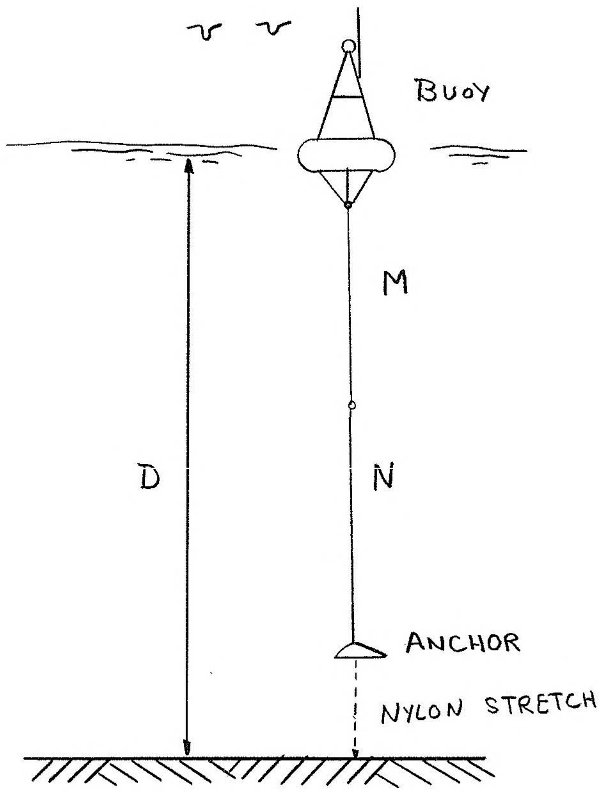


Figure 48.

If D is the water depth, M the total length of all metallic components (wire rope, chain, instrument casings, etc.) and N the unstretched length of all elastic components (nylon rope), then "α" the % elongation of the elastic components is given by

$$\alpha = \frac{D - (M + N)}{N}$$

When the desired preset tension is known as a percentage of the breaking strength of the nylon used, the corresponding value of α is found from the second branch of the hysteresis loop of the loading cycle.

The total length of unstretched nylon to use in the mooring is then given by

$$N = \frac{D - M}{1 + \alpha}$$

APPENDIX 5-3

1968 SHALLOW WATER TEST - CONTROL CHART

(AS OF MARCH 1969)

BUOY CODE LETTER	TYPE OF MOORING	DESCRIPTION OF SAMPLE	DATE SET	DATE REPORT MISSING	DAYS ON STATION	RECOVERY OF PARTS ADRIFT: WHAT	RECOVERY OF PARTS ADRIFT: WHEN	RECOVERY OF PARTS ADRIFT: WHERE	RECOVERY OF PARTS ADRIFT: BY	RECOVERY OF PARTS LEFT ON STATION: WHAT	RECOVERY OF PARTS LEFT ON STATION: WHEN	RECOVERY OF PARTS LEFT ON STATION: HOW	FAILURE IDENTIFICATION	REMARKS
A-1	PILOT	1/4" 1X19 G.A.C. WITH JACKET & BOOTS 8200 POUNDS BREAKING STRENGTH	MARCH 15, 1968		19					MARKER BUOY, TORROID PART OF WIRE WEIGHT, TENSIOMETER, CHAIN, ANCHOR	APRIL 3, 1968 APRIL 5, 1968	C'N BILL NORMAL C'N BILL DRAGGING	WIRE ROPE PARTED DURING HAULING	GROUND CHAIN FROM MARKER ANCHOR TO MAIN ANCHOR FOUND IN TWO PIECES
A-2	CORNER W/ LIGHT	NO SAMPLE ALL CHAIN	APRIL 3, 1968		301					BUOY, ALL 1/2" CHAIN, 1000 LB WT., ALL 1 1/2" CHAIN & ANCHOR	JAN 29 1969	C'N BILL NORMAL	NO FAILURE	
B-1	TEST	1/4" 7X19 G.A.C. WITH JACKET & BOOTS 7000 POUNDS R.B.S.	APRIL 8 1968		296					BUOY, SAMPLE, ALL 1/2" CHAIN, 1000 LB. WT., 1 1/2" CHAIN & ANCHOR	JAN 29 1969	C'N BILL NORMAL	NO FAILURE	
C-1	TEST	1/4" 1X19 G.A.C. WITH JACKET & BOOTS 8200 POUNDS R.B.S.	APRIL 9, 1968	JAN. 10, 1969	276					1/2" CHAIN, 1 1/2" CHAIN, ANCHOR	JAN 29 1969	C'N BILL NORMAL	FAILURE OF SHACKLE BELOW WEIGHT	BUOY, SAMPLE & WEIGHT NOT RECOVERED
D-1	TEST	1/4" 1X19 G.A.C. WITH JACKET & BOOTS 8200 POUNDS R.B.S.	APRIL 10, 1968		294					BUOY, SAMPLE, 1/2" CHAIN, 1000 LB. WEIGHT, 1 1/2" CHAIN & ANCHOR	JAN 29 1969	C'N BILL NORMAL	NO FAILURE	
E-1	CORNER W/ LIGHT	NO SAMPLE ALL CHAIN	APRIL 11, 1968		293					BUOY, ALL 1/2" CHAIN, 1 1/2" CHAIN & ANCHOR	JAN 30 1969	C'N BILL NORMAL	NO FAILURE	
F-1	TEST	1/4" 7X19 G.A.C. WITH JACKET & BOOTS 7000 POUNDS R.B.S.	APRIL 8, 1968	NOV 21, 1968	227	BUOY & 20' WIRE SAMPLE	NOV 22, 1968	MARTHA'S VINEYARD		ANCHOR, LENGTH OF 1/2" CHAIN & LENGTH OF 1 1/2" CHAIN	DEC 27 1968	C'N BILL DRAGGING	1- WIRE CHAFING 2- 1/2" CHAIN: COTTER PIN OF SHACKLE BETWEEN TWO LENGTHS OF 1/2" CHAIN OR CHAFING & CORROSION OF CHAIN @ THE MUD LINE	WEIGHT NOT RECOVERED - CHAFING OF WIRE SUBSEQUENT TO FAILURE OF CHAIN BUOY NOT RETURNED
G-1	TEST	1/4" 1X19 UHS. WITH JACKET & BOOTS 13,000 POUNDS R.B.S.	APRIL 10, 1968	NOV 21, 1968	225					ANCHOR, LENGTH OF 1 1/2" CHAIN, LENGTH OF 1/2" CHAIN (TERMINATED BY SHACKLE)	DEC 31 1968	C'N BILL DRAGGING	COTTER PIN OF SHACKLE BETWEEN TWO LENGTHS OF 1/2" CHAIN @ THE MUD LINE	CHAIN SEVERELY PITTED @ MUD LINE NUMBER OF COTTER PINS SEVERELY DAMAGED BUOY, SAMPLE & WEIGHT NOT RECOVERED
H-1	TEST	1/4" 1X19 U.H.S. WITH JACKET & BOOTS 13,000 POUNDS R.B.S.	APRIL 10, 1968	AUG. 12, 1968	124	BUOY, SAMPLE WEIGHT & 40' OF 1/2" CHAIN	AUG. 19, 1968	2 MILES WEST OF FARM	A II	ANCHOR, LENGTH OF 1 1/2" CHAIN, LENGTH OF 1/2" CHAIN	DEC 27 1968	C'N BILL DRAGGING	COTTER PIN OF SHACKLE BETWEEN TWO LENGTHS OF 1/2" CHAIN @ THE MUD LINE	CHAIN SEVERELY PITTED - NUMBER OF COTTER PINS SEVERELY DAMAGED
I-1	TEST	1/4" 1X43 GAC. WITH JACKET & BOOTS 8000 POUNDS R.B.S.	APRIL 10, 1968		294					BUOY, SAMPLE, ALL 1/2" CHAIN, 1000 LB. WEIGHT, 1 1/2" CHAIN & ANCHOR	JAN 29 1969	C'N BILL NORMAL	NO FAILURE	
J-1	TEST	1/4" 1X43 GAC WITH JACKET & BOOTS 8000 POUNDS R.B.S.	APRIL 12, 1968	DEC 20, 1968	252	BUOY, SAMPLE, WEIGHT, 2' OF 1/2" CHAIN, SHACKLE & SLING	JAN 7, 1969	40°-23.0'N 68°-13.5'W	A II	ANCHOR, LENGTH OF 1 1/2" CHAIN LENGTH OF 1/2" CHAIN (TERMINATED BY SHACKLE & SLING RING)	DEC 27 1969	C'N BILL DRAGGING	FAILURE OF COTTER PIN OF SHACKLE @ BOTTOM OF WEIGHT	BUOY WASHED OVERBOARD BY HEAVY SEAS JAN 9 - 1969
K-1	TEST	9/32" 3X19 WITH JACKET AND BOOTS 9000 LB. R.B.S.	APRIL 8, 1968	OCT 10, 1968	185	BUOY & 82' WIRE SAMPLE	NOV 20, 1968	30 MILES S.W. OF NANTUCKET LIGHTSHIP	MAJ. CASSEY (FISH BOAT)	ANCHOR, LENGTH OF 1 1/2" CHAIN, ALL OF 1/2" CHAIN	OCT 21 1968	C'N BILL DRAGGING	COTTER PIN OF SHACKLE ON BOTH SIDES OF WEIGHT	WEIGHT NOT RECOVERED - CHAIN PITTED - COTTER PINS DAMAGED (BUT NOT NEAR ANCHOR)
L-1	TEST	1/4" 7X19 GAC WITH JACKET & BOOTS 7000 POUNDS R.B.S.	APRIL 9, 1968	DEC 27, 1968	262					ANCHOR, LENGTH OF 1 1/2" CHAIN, LENGTH OF 1/2" CHAIN	DEC 27 1968	C'N BILL DRAGGING	COTTER PIN OF SHACKLE BETWEEN TWO LENGTHS OF 1/2" CHAIN @ THE MUD LINE	SEVERE CORROSION OF CHAIN & COTTER PINS BUOY, SAMPLE & WEIGHT NOT RECOVERED
M-1	TEST	1/4" 7X19 INCONEL - BARE 7000 POUNDS R.B.S.	APRIL 10, 1968		294					BUOY, SAMPLE ALL 1/2" CHAIN, 1000 LB. WEIGHT, 1 1/2" CHAIN & ANCHOR	JAN 29 1968	C'N BILL NORMAL	NO FAILURE	LARGE GROWTH OF MOSSELS - FISH HOOKS IN THE SAMPLE.
N-1	TEST	1/4" 1X19 GAC WITH JACKET & BOOTS 8200 POUNDS R.B.S.	APRIL 11, 1968	NOV. 21, 1968	224					ANCHOR, LENGTH OF 1 1/2" CHAIN, ALL OF 1/2" CHAIN (TERMINATED BY SHACKLE & SLING RING)	DEC 27 1968	C'N BILL DRAGGING	FAILURE OF COTTER PIN OF SHACKLE @ BOTTOM OF WEIGHT	BUOY, SAMPLE & WEIGHT NOT RECOVERED
O-1	TEST	1/4" 7X19 GAC WITH JACKET & BOOTS 7000 POUNDS R.B.S.	APRIL 12, 1968	APRIL 29, 1968	17	BUOY, SAMPLE & WEIGHT	APRIL 30, 1968	3 MILES SSW OF GAY HEAD	C'N BILL	ANCHOR, LENGTH OF 1 1/2" CHAIN ALL OF 1/2" CHAIN TERMINATED BY SHACKLE	APRIL 30, 1968	C'N BILL DRAGGING	FAILURE OF COTTER PIN OF SHACKLE @ BOTTOM OF WEIGHT	
O-2	TEST	SAME AS O-1	MAY 2, 1968	SEPT 20, 1968	141	BUOY, SAMPLE, WEIGHT & 25' OF 1/2" CHAIN	SEPT 24, 1968	OFF BUOY FARM	A II	ANCHOR, LENGTH OF 1 1/2" CHAIN, 95' OF 1/2" CHAIN WITH SHACKLE	SEPT. 30, 1968	C'N BILL DRAGGING	FAILURE OF COTTER PIN OF SHACKLE BETWEEN TWO LENGTHS OF 1/2" CHAIN @ THE MUD LINE	ALL SHACKLES WELDED ONBOARD C'N BILL BEFORE SETTING - WELD WAS OPENED UP ON SHACKLE @ BITTER END - CHAIN PITTED
P-1	CORNER W/ LIGHT	NO SAMPLE ALL CHAIN	APRIL 3, 1968		301					BUOY, ALL 1/2" CHAIN, 1 1/2" CHAIN, ANCHOR	JAN 30, 1969	C'N BILL NORMAL	NO FAILURE	
Q-1	TEST	9/32" 3X19 W/JACKET & BOOTS 9000 LBS. R.B.S.	APRIL 9, 1968		295					SAMPLE & TENSIOMETER (SAMPLE & TENSIOMETER REPLACED)	JULY 13, 1968	C'N BILL NORMAL	NO FAILURE	LARGE AMOUNT OF GROWTH ON WIRE SAMPLE & TENSIOMETER BUT NOT ON PAINTED BOTTOM OF BUOY
Q-2	TEST	SAME AS Q-1	JULY 13-1968		100					BUOY, SAMPLE, TENSIOMETER WEIGHT, 1/2" CHAIN, 1 1/2" CHAIN & ANCHOR	OCT 21 1968	C'N BILL NORMAL	NO FAILURE	SEVERE CORROSION OF CHAIN & COTTER PINS - LARGE GROWTH
R-1	TEST	1/4" 1X19 GAC WITH JACKET & BOOTS 8200 POUNDS R.B.S.	APRIL 10, 1968		294					BUOY, SAMPLE, ALL 1/2" CHAIN, 1000 LB. WT. 1 1/2" CHAIN & ANCHOR	JAN 30 1969	C'N BILL NORMAL	NO FAILURE	SEVERE CORROSION OF CHAIN & COTTER PINS - LARGE GROWTH
S-1	TEST	1/4" 7X19 INCONEL - BARE 7000 POUNDS R.B.S.	APRIL 11, 1968	OCT. 10, 1968	182	BUOY, 1' SAMPLE (SAMPLE CUT BY RETRIEVING PARTY)	OCT 17, 1968	MONTAUK POINT N.Y.	U.S.C.G.	ANCHOR, 1 1/2" CHAIN 130' 1/2" CHAIN (TERMINATED BY SHACKLE & SLING RING)	OCT 21, 1968	C'N BILL NORMAL	FAILURE OF COTTER PIN OF SHACKLES @ BOTTOM OF WEIGHT	WEIGHT NOT RECOVERED
T-1	CORNER W/ LIGHT	NO SAMPLE ALL CHAIN	APRIL 11, 1968		294					BUOY, ALL 1/2" CHAIN, 1 1/2" CHAIN, ANCHOR	JAN 30, 1969	C'N BILL NORMAL	NO FAILURE	CORROSION OF CHAIN & COTTER PINS - GROWTH

APPENDIX NO. 5.4

RESULTS OF THE VISUAL INSPECTION & PULL TESTING OF WIRE ROPE & CHAIN SAMPLES RETRIEVED FROM THE 1968 SHALLOW WATER TEST ARRAY

STA. CODE	DESCRIPTION OF SAMPLE	DAYS ON STA.	BREAKING STRENGTH			LOCATION OF BREAK	OBSERVATIONS
			RATED	TESTED	%REDUCT.		
A-0							
A-1	½"Chain-mud line	301	23,0001b.	13,300 lb.	42%	Point of Contact Between Links	Started to yeild @ 5000 lbs. Chain badly pitted, corroded.
B-1	¼"7x19 GAC w/Jacket & Boot	296	7,0001b.	7,620 lb.	N/A	¼" Outside of factory Termination	No Corrosion in Boot
	¼"7x19 GAC w/Jacket & Boot	296	7,0001b.	7,850 lb.	N/A	Outside of factory Boot (damaged @ sea)	No Corrosion in Boot Corrosion in damaged area
	¼"7x19 GAC w/Jacket	296	7,0001b.	7,705 lb.	N/A	¼" from WHOI termination	
D-1	¼"1x19 GAC w/Jacket & boot	294	8,2001b.	9,930 lb.	N/A	¼" Inside WHOI swage Termination	No Corrosion in Boot
	¼"1x19 GAC w/Jacket & Boot	294	8,2001b.	10,130 lb.	N/A	At end of factory Termination	No Corrosion in Boot
	¼"1x19 GAC w/Jacket	294	8,2001b.	9,940 lb.	N/A	At end of WHOI Termination	

E-1	½" Chain-mud line	293	23,000lb.	15,250 lb.	34%	At Point of Contact Between links	Started to yield @ 4,800 lb. Chain badly pitted & corroded
F-1	¼"7x19 GAC w/Jacket & boot	227	7,000lb.				
	¼"7x19 GAC w/Jacket & boot	227	7,000lb.				
	¼"7x19 GAC w/Jacket	227	7,000lb.				
H-1	¼"1x19 UHS w/Jacket & boot	124	13,000lb.	8,000 lb.	N/A	Sample pulled from WHOI fitting	Wire not corroded, termination excellent
	¼"1x19 UHS	124	13,000lb.	8,000 lb.	N/A	Sample pulled from WHOI fitting	Wire not corroded, termination excellent
	½"Chain below 1,000 lb. wt.	124	23,000lb.	22,150 lb.	3%	Point of Contact Between Links	Chain Severly pitted
I-1	¼"1x43 GAC w/Jacket & boot	294	8,000lb.	10,820 lb.	N/A	Broke 3/4" inside WHOI termination	No Corrosion in boot
	¼"1x43 GAC w/Jacket	294	8,000lb.	10,800 lb.	N/A	Broke ¼" inside WHOI Termination	
	¼"1x43 GAC w/Jacket & Boot	294	8,000lb.	10,770 lb.	N/A	Broke at Mouth of WHOI Termination	No Corrosion in Boot

J-1	½" Chain in water	252	23,0001b	18,200 lb.	24%	Broke at weld of top link	No Corrosion-Galv. Coat still on
	½" Chain in water	252	23,0001b.	22,500 lb.	2%	Broke at weld of link	No Corrosion-Galv. Coat still on
	½" Chain mud line	252	23,0001b.	13,050 lb.	43%	Broke at weld of link	Badly Corroded, Deep Pits
	½" Chain mud line	252	23,0001b.	10,550 lb.	54%	Broke at weld of link	Badly Corroded, Deep Pits
K-1	9/32" 3x19 swaged alum. w/Jacket & boot	185	9,0001b.	8,960 lb.	N/A	Broke at face of Grip	Wire Held in Grips Boots leak: Corrosion in Fitting.
	9/32" 3x19 swaged alum. w/Jacket & boots	185	9,0001b.	9,160 lb.	N/A	Broke at face of Grip	Wire Held in Grips Boots leak: Corrosion in Fitting
L-1	½" Chain- bitter end	262	23,0001b.	19,250 lb.	16%	Broke at Point of Contact Between Links	Some pitting around max bend radi of links
	½" Chain next to B.E.	262	23,0001b.	19,500 lb.	15%	Broke at Point of Contact Between Links	Some Pitting around max bend radi of links
M-1	¼"7x19 Inconel Bare-No Boots	294	7,0001b.	6,850 lb.	2%	Broke 3/4" inside factory termination	Wire in Excellent Condition (visually)

	¼"7x19 Inconel Bare-No Boots	294	7,000lb.	4,950 lb.	29%	Broke @ Center of Sample	Wire Fishooked at point of Break
	¼"7x19 Inconel Bare-No Boots		7,000lb.	7,330 lb.	N/A	Broke at Beginning of WHOI termination	Wire in Excellent Condition (visually)
N-1	½" Chain-below weight	224	23,000lb.	19,450 lb.	16%	Broke at Weld of link	Galvanizing still present
	½" Chain-below weight	224	23,000lb.	23,200 lb.	N/A	Broke at Weld of link	Galvanizing still present
O-2	¼"7x19 GAC w/ Jacket & boot	141	7,000lb.	7,890 lb.	N/A	Broke 1' from end of factory termination	Some Corrosion in wire boot. Watertight.
	¼"7x19 GAC w/ Jacket & boot	141	7,000lb.	7,770 lb.	N/A	Broke 1' from end of factory termination	Boot leaked-Jacket ruptured.
	¼"7x19 GAC w/ Jacket & boot	141	7,000lb.	7,840 lb.	N/A	Broke 1' from end of WHOI termination	Wire in Good condition
	½" Chain-below weight	141	23,000lb.	18,250 lb.	20%	Broke @ point of contact between links	Chain Severly pitted
P-1	½" Chain @ Mud Line	301	23,000lb.	14,200 lb.	38%	Broke @ point of contact Between links	Chain pitted & worn
Q-1	9/32" 3x19 swaged w/Jacket & boot	295	9,000lb.	10,200 lb.	N/A	Broke @ factory termination	Boot & jacket damaged wire in good condition
	9/32" 3x19 swaged w/Jacket & boot	295	9,000lb.	10,300 lb.	N/A	Broke @ factory termination	Boot & jacket damaged. Wire in good condition
Q-2	9/32" 3x19 swaged w/ jacket & boot	100	9,000lb.	6,900 lb.	23%	Broke @ Middle of sample	@ Break, Jacket Broken & wire severly corroded.

	9/32" 3x19 swaged w/ Jacket & boot	100	9,000lb.	9,010 lb.	N/A	Broke @ Grip face	One end held by grip.
R-1	¼" 1x19 GAC w/Jacket & boot	294	8,200lb.	8,270 lb.	N/A	Pulled out of WHOI fitting	Boots Leaked-no great amount of corrosion.
	¼"1x19 GAC w/Jacket & boot	294	8,200lb.	8,340 lb.	N/A	Broke 3/4" inside WHOI fitting	Boots Leaked-no great amount of corrosion.
	¼"1x19 GAC w/Jacket	294	8,200lb.	8,370 lb.	N/A	Pulled out of WHOI fitting	
T-1	½" Chain @ mud line	294	23,000lb.	14,500 lb.	37%	Broke @ pt. of contact between links	Chain pitted & corroded.

APPENDIX 5.5

TELEMETRY BUOY DATA SHEET

SHAPE:	Low drag flat conical disc
DIMENSIONS:	Hull. 11 ft. 8 in. diameter by 3 ft. 7 in. high Deck slope: 1 inch in 2 feet Side slope: 5 inches in 1 foot Tower. 14 ft. 4 in. high
MATERIAL	Aluminum 6061-T6
WEIGHT	Structure (Hull & Tower): 2000 lbs. Foam: 500 lbs. Total: 2500 lbs.
DISPLACEMENT:	When totally submerged the weight of the seawater displaced is 15,000 lbs.
MAXIMUM BUOYANCY:	12,500 lbs.
RIGHTING MOMENT:	A strong positive righting moment is developed up to 90° from horizontal. The buoy is very stable in water, but rides "stiff". Natural period of oscillation: Roll: 2.2 sec. Heave: 1.2 sec.
STRUCTURAL	Hull. The hull of the buoy is made of plates welded to an internal frame structure. The deck and bottom plates are 1/8" thick (6 around). The side plates are 3/8" thick (3 around). The internal frame is made of 12 channel beams 3" x 1.73 lb. welded to the central well plates and the hull side plates (6 around). Three reinforced lifting lugs and three legs one in. thick welded to the framework and the central well complete the structure of the hull. The hull is divided by 1/8 in. thick bulkhead plates into 3 leak-tight compartments. Furthermore, these compartments are filled with polyurethane foam.

Central Well. The instrumentation central well is 3 ft. 11 in. in diameter by 2 ft. high. It is made of 1/4 in. thick plates. The bottom of the well has a grid for instrumentation attachment. At the lowest point of the buoy a smaller well 1 ft. in diameter by 11 in. high is provided for housing lead ballast if necessary. The central well is closed with a 3 ft. diameter hatch with wing nuts and neoprene gasket.

Connector Wells. One connector well installed on the deck and one at the bottom of the hull permit penetration into the central well through elbows. In this way, mechanical and electrical penetrators can be added at will without puncturing the deck plates or the hatch cover plate.

Tower. The tripod tower is made of 4" x 2.50 lbs. aluminum channels. Six (6) braces hold the legs together. Two legs support 6 grabbing rings, one leg is a ladder. Instrumentation can be placed at three levels in the tower: top, middle, and lower levels. The tower is removable and when used is bolted to the three lugs of the hull, (use insulation bushings). Electrical harness of the tower should be disconnected at the connector well-plate. The structure is painted international orange, the well is painted white.

HANDLING

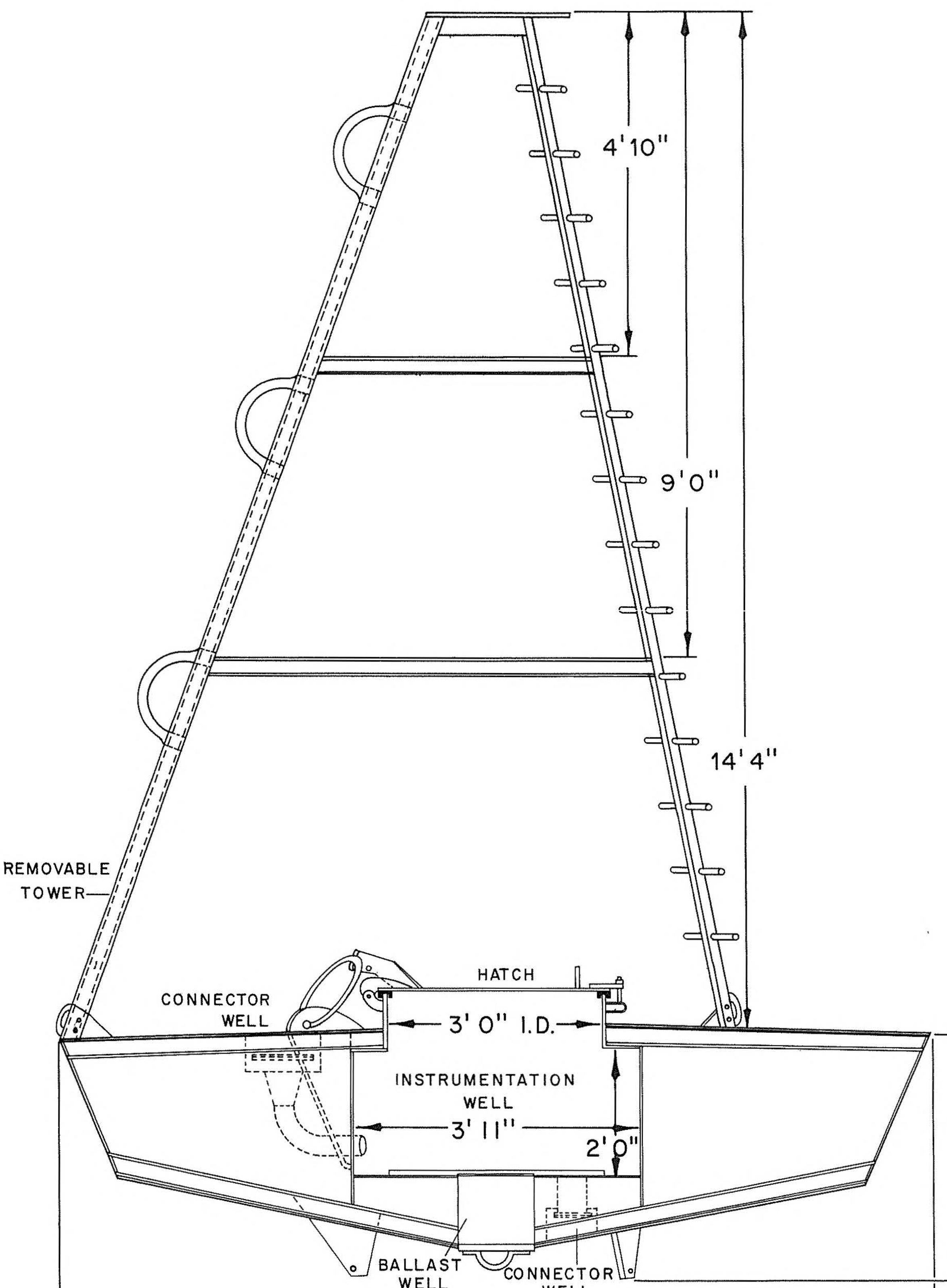
Lifting. IMPORTANT: the lifting must be made from the lifting rings and not from any other point. One, two, or three rings may be used. When lifting from one ring, the deck of the buoy will be approximately 10° from the vertical. The crane cable will clear all instruments and antennae. When placed in a moderate sea on its side, the buoy will right itself up in the normal position.

Grabbing. Grabbing can be done from the rings on the tower legs or from the lower ring (no lift, no mooring line attachment).

Storing. The buoy should be stored on its 3 legs. It can be lashed down from tower lugs on the deck of the buoy. The hatch should always be closed during storage.

Mooring Attachment. The mooring should be attached to a flexible or rigid bridle connected to the three 1 inch thick steel lugs bolted to the aluminum legs.

This buoy was designed at the Woods Hole Oceanographic Institution by H. O. Berteaux, Department of Ocean Engineering.


4'10"
9'0"
14'4"
REMOVABLE
TOWER
HATCH
CONNECTOR
WELL
3' 0" I.D.
INSTRUMENTATION
WELL
3' 11"
2' 0"
3' 7"
BALLAST
WELL
CONNECTOR
WELL
11' 8"

APPENDIX NO. 5.6

PREFORMED LINE PRODUCTS COMPANY
RESEARCH AND ENGINEERING

FINAL TEST REPORT

LABORATORY FATIGUE TESTS OF ¼" 1x19 GALVANIZED AIRCRAFT CABLE CONDUCTED FOR WOODS HOLE OCEANOGRAPHIC INSTITUTION PROJECT NO. 67176

ABSTRACT

A wire rope testing program was initiated by Woods Hole Oceanographic Institution to provide experimental data necessary to evaluate the relative merits of different wire rope construction and assemblies.

The type of fatigue tests performed were selected because they simulated the type and magnitude of loading a buoy mooring system would encounter during actual field use. These tests were:

Cyclic Tension
Cyclic Impact
Vibration.

The results indicate that vibration will not be a problem with this type of buoy mooring configuration. The most damaging stress results from impact loading.

The accumulation and graphical representation of the data assembled from this series of tests will allow comparisons to be made in the future between the old and the new. This comparison will be a basis for evaluation so that the best assemblies can be selected for use in buoy mooring line systems.

E. A. Capadona
Administrator-Contact Testing

Preformed Line Products Company
Research & Engineering
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Cleveland, Ohio

PREFORMED LINE PRODUCTS COMPANY
RESEARCH AND ENGINEERING

January 29, 1969

FINAL TEST REPORT

LABORATORY FATIGUE TESTS OF ¼" 1x19 GALVANIZED AIRCRAFT CABLE CONDUCTED FOR WOODS HOLE OCEANOGRAPHIC INSTITUTION PROJECT NO. 67176

Objectives

To obtain data indicative of fatigue characteristics of the 1x19 strand and to establish a basis of reference on which to judge the relative merits of other wire rope samples to be tested in the future.

General Outline of Test Program

Three types of mechanical fatigue tests were conducted on the buoy mooring rope. This strength member consisted of ¼" 1x19 Galvanized Steel Aircraft Cable. The strand had a plastic jacket and a tapered boot over the dead-end shank. The tests investigated separately the dynamic loads which result in fatigue failure of the wire rope.

The selected values of the test loads were based on measurements made at sea and on analysis of the forcing functions. The test parameters were intended to duplicate a range of conditions which the mooring system encountered at sea. Each test was repeated twice unless the results obtained differed by more than 15%, in which case a third test was performed.

The type of tests performed were cyclic tension, cyclic impact, and vibration fatigue.

Project Plan

Cyclic Tension Test

This series of tests simulated the cyclic variations, around a mean, of the longitudinal tension due to wave action. The rate of application in the range of the mean tensions are representative and compatible with measurements made at sea. It was anticipated that the event would give the endurance life of the samples tested for each particular test parameter.

Cyclic Impact Test

This series of tests tend to simulate the rapid rise, high-energy impact loading imposed on the mooring cable due to buoy motion during severe sea conditions.

Vibration Test

This test simulated the strumming conditions induced by vortex shedding of taut mooring lines implanted in strong currents.

Test Parameters

Cyclic Tension

Each sample to be tested was ¼" 1x19 Galvanized Steel Aircraft Cable with a rated breaking strength of 8,200 pounds. The 1/32"-thick-polyethylene jacket and the tapered boots over the shank of the swaged end fittings were eliminated in this series of tests. The length of the sample was 20 feet ± 2 inches. The test samples were dynamically tensioned according to the following table:

Mean Tension (lbs)	Variation (lbs)	Period Sec/Cycle
4,000	± 1,250	8
3,000	± 1,000	7
2,000	± 750	6
1,000	± 500	5

Each test specimen was installed in the cyclic tension machine and automatically cycled around the mean tension as indicated in the above chart.

Cyclic Impact

Each sample to be tested was ¼" 1x19 Galvanized Steel Aircraft Cable with the rated breaking strength of 8,200 pounds. The 1/32" polyethylene jacket and the tapered boots over the shank of the swaged end fittings were eliminated for this test. Sample lengths were 12 feet, 7 inches ±1 inch. The samples were dynamically tensioned according to the following table:

Static Load (lbs)	Peak Load (lbs)	Period Sec/Cycle
2,000	4,000	3
1,500	3,000	3
1,000	2,000	3

Minimum tension for the tests were 50 pounds. Each sample was installed on the cyclic impact machine and automatically loaded to the maximum peak load as indicated in the above chart. The loading was continued until a failure occurred. In each case the test was considered completed after the first wire failure or any failure of the swaged end fittings.

Vibration Test

Samples to be tested were ¼" 1x19 Galvanized Steel Aircraft Cable with the rated breaking strength of 8,200 pounds. The cable was covered with a 1/32" wall thickness of polyethylene jacket and a molded boot was installed over the swaged end fitting. The length of the samples were 120 feet ± 6 inches. Other test parameters were:

Tension	2,000 pounds
Frequency	82 cps
Amplitude	.350±inches (peak-to-peak)
Free Span Length	110 feet
Span Angle	0°
Loop Length	59½ inches (average)

Each test specimen was installed and tensioned to the test load and allowed to remain at this tension for a 24-hour period before the test was started. Upon completion of this 24-hour period, the north end was clamped down to prevent the eye from pivoting and the test was started. Vibration was induced by an electromechanical shaker motor which was adjusted along the span to provide an optimum performance as to range of amplitude and energy requirements to maintain a steady-state resonant condition. The final location of the vibration motor was at 93 feet, 6 inches from the north fitting and the final test frequency selected to maintain resonant conditions was 82 cps.

The tests were conducted 24 hours a day and over the weekend when possible. A technician observed the tests periodically during the working hours. Proper vibratory conditions were maintained with a span control system. Test amplitude was monitored during weekend operation. A test was considered completed after one wire failed or 200 million cycles, whichever occurred first.

Results

Results of the cyclic tension tests, the cyclic impact tests, and the vibration tests are tabulated in Tables I, II and III.

TABLE I

CYCLIC TENSION TEST

¼" 1x19 GAC (BARE) RBS 8,200 POUNDS

SPECIMEN LENGTH -- 20',1"

Test No.	Load Range (lbs)	Sec/Cycle	*Cycles to First Wire Failure	Time	*Total Cycles at End of Test	Remarks
1.	2,750 - 5,250	8	23,700	2 days, 5 hours	30,700	One outer-wire failure.
2.	2,750 - 5,250	8	19,000	1 day, 18 hours	29,400	Two outer-wire failures.
2A.	2,750 - 5,250	8	17,400	1 day, 14 hours	17,400	Confirming test. One outer-wire failure.
3.	2,000 - 4,000	7	48,200	3 days, 22 hours	74,600	Two outer-wire failures.
4.	2,000 - 4,000	7	51,100	4 days, 3 hours	65,400	Two outer-wire failures.
4A.	2,000 - 4,000	7	49,200	4 days	49,200	Confirming test. One outer-wire failure.
5.	1,250 - 2,750	6	99,000	6 days, 21 hours	103,800	Two outer-wire failures.
6.	1,250 - 2,750	6	102,400	7 days, 3 hours	110,100	Two outer-wire failures.
6A.	1,250 - 2,750	6	89,500	6 days, 5 hours	89,500	Confirming test. One outer-wire failure.
7.	500 - 1,500	5	106,900	6 days, 4 hours	118,700	One outer-wire failure.
8.	500 - 1,500	5	187,600	10 days, 21 hours	187,600	one outer-wire failure.
9.	500 - 1,500	5	99,200	5 days, 18 hours	99,200	Confirming test. One outer-wire failure.

*To the nearest 100 cycles.

TABLE II

CYCLIC IMPACT TEST

¼" 1x19 GAC (BARE) RBS 8,200 POUNDS

SPECIMEN LENGTH -- 12',8"

Test No.	Static Load	Load Range (lbs)	Sec/Cycle	*Total Cycles	Time	Remarks
1.	2,000	50 - 4,000	6	1,700	3.0 hours	Eight wire failures inside end fitting.
2.	2,000	50 - 4,000	6	1,000	2.0 hours	One outer-wire failure outside end fitting.
3.	2,000	50 - 4,000	6	800	1.6 hours	One wire failure inside end fitting.
4.	1,500	50 - 3,000	3	8,300	7.0 hours	One wire failure inside end fitting.
5.	1,500	50 - 3,000	3	4,200	3.5 hours	One wire failure inside end fitting.
6.	1,500	50 - 3,000	3	11,200	9.0 hours	One wire failure inside end fitting.
7.	1,000	50 - 2,000	3	48,800	41.0 hours	One wire failure inside end fitting.
8.	1,000	50 - 2,000	3	29,200	25.0 hours	Three wires failed outside end fitting.
9.	1,000	50 - 2,000	3	16,300	14.0 hours	One wire failure at edge of end fitting.

*To the nearest 100 cycles.

TABLE III

AEOLIAN VIBRATION TEST

¼" 1x19 GAC (JACKETED) RBS 8,200 POUNDS

(Polyethylene Jacket and Molded Boots on End Fittings)

Free Span Length	93 feet
Tension	2,000 pounds
Frequency	82 ± 1 cps
Amplitude	.350 inches (peak-to-peak)

Test No.	Total Cycles	Time	Observations
1.	216,600,000	30 days, 14 hours	No visible indication of failures during or at termination of test. *X-ray inspection at indicated intervals revealed no failures.
2.	200,100,000	28 days, 6 hours	No visible indication of failures during or at termination of test. *X-ray inspection at indicated intervals revealed no failures.

*X-ray inspections of the area at the clamped end fitting (Fig. 27) were made at 0, 10, 20, 50, 75, 100, 125, 175, and 200 million cycles.

Conclusions

The results of these tests indicate that the most critical characteristics (weakness) of this system is failure due to stresses developing from impact loading. The next most critical stress results from cyclic tension.

From these observations, it is noted that absolute care must be taken to avoid over stressing from impact loading especially during launching procedures. The total system should be designed so that some method of stress dampening can be inserted in the system and activated upon the occurrence of a rapid stress rise. This could very well be a shock or energy absorber.

It is quite evident that the lower the peak loads the lower the mean load about which the system cycles, the longer the life of the system. Unfortunately, this parameter is uncontrollable and at the mercy of the sea.

The next critical stress rising is from cyclic tension which is a slower stress riser due to the rise and fall of the surface buoy. It is reasonable to assume that should a shock absorber be adopted for impact loading, then this could very well take care of the cyclic tension problem. It is, therefore, recommended that two types of solutions be investigated.

1. A method of decouple the mooring line from the surface excitation.

2. Investigate various wire rope construction so that a larger safety factor can be included to reduce the percentage of loading on the cable.

Vibration testing should be discontinued at this time. Vibration testing should be a final quality assurance type test after a new design is proven in the more critical stress conditions of impact and cyclic tension.

A visual inspection of the broken ends indicated that the fractures were fatigue failures in both cyclic tension and cyclic impact. There was some evidence that the failures began at some indentation on the surface of the broken wire. A macroscopic investigation should confirm or disprove this observation.

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ANALYSIS & EXPERIMENTAL EVALUATION OF SINGLE POINT MOORED BUOY SYSTEMS by H. O. Berteaux and P. G. Walden. approx. 100 pages. May 1969. N00014-66-C0241, NR 083-004.

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1. Engineering Evaluation of Buoy Systems
2. Mooring Line Components
3. Deep-sea Buoys

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